RADIO RECEIVING TUBES

OTHER BOOKS
BY
THE AUTHORS

Moyer and Wostrel—
PRACTICAL RADIO

Moyer and Wostrel—
PRACTICAL RADIO CONSTRUCTION AND REPAIRING

RADIO RECEIVING TUBES

INCLUDING APPLICATIONS FOR DISTANT CONTROL OF INDUSTRIAL PROCESSES AND PRECISION MEASUREMENTS

BY

JAMES A. MOYER, S.B., A.M.

Director of University Extension, Massachusetts Department of Education, Member of American Institute of Electrical Engineers; Fellow of the American Association for the Advancement of Science; Fellow of the Royal Society of Arts; Mitglied des Vereines Deutscher Ingenieure; Membre Titulaire Association Internationale du Froid; Member of the Franklin Institute; American Society of Mechanical Engineers; Society of Automotive Engineers

AND

JOHN F. WOSTREL

Instructor in Radio Engineering, and Supervisor in Charge of Industrial Subjects, Division of University Extension, Massachusetts Department of Education

FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK: 370 SEVENTH AVENUE
LONDON: 6 & 8 BOUVERIE ST., E. C. 4
1929

PRINTED IN THE UNITED STATES OF AMERICA

THE MAPLE PRESS COMPANY, YORK, PA.

PREFACE

Until the invention of printing, the communication of news and ideas was accomplished almost entirely by word of mouth. Thereafter, the avenues of communication were broadened enormously, and as a result the eye supplanted the ear as the principal external medium for the reception of ideas. With the present development of radio devices, the ear has come into its own again. Sound borne upon radio waves transcends space and transcontinental communication is commonplace. This remarkable accomplishment owes much to the vacuum tube, the most essential part of all radio apparatus.

In a comparatively short time, there has been a great increase in the use of vacuum tubes for radio purposes. Concurrently, popular interest in a practical knowledge of radio principles and radio operation has greatly increased.

In this book the essential principles underlying the operation of vacuum tubes are explained in a manner calculated to present a well defined picture to students and general readers. The vacuum tube possesses a remarkable variety of functions and, accordingly, this book includes, in addition to the use of two- and three-element vacuum tubes for radio reception and transmission, other applications that are of considerable practical significance. These additional applications include the remote control of airplanes and sea-going vessels by the use of instruments which employ vacuum tubes in essential capacities, as well as methods of applying vacuum tubes to the remote control of humidity and similar uses. The first chapter of the book is introductory; its purpose is to outline briefly some present theories concerning the flow of electrons from highly heated bodies to those which are relatively cool.

The authors wish to express their appreciation of the assistance they have received from Mr. Glenn H. Browning of the

Browning-Drake Corporation and Mr. Horatio Lamson of the General Radio Company, and to acknowledge the contributions made by the Radio Corporation of America, the General Electric Company, the New England Telephone and Telegraph Company and E. T. Cunningham, Inc.

THE AUTHORS.

BOSTON, MASSACHUSETTS.
February, 1929.

CONTENTS

RADIO RECEIVING TUBES

CHAPTER I

INTRODUCTION

History of the Development of Radio Vacuum Tubes.—For more than two hundred years the fundamental phenomena associated with the present use of radio vacuum tubes have been known to scientists.[1] These phenomena depend on the ability of very hot bodies to discharge electricity at moderate voltages through the surrounding air, which thus acquires electrical conductivity. A white-hot platinum wire, for example, when placed in an atmosphere where the pressure is very low will charge negatively an electrode which may be nearby. This phenomenon is due to the emission of negative *ions*[2] from the hot platinum wire.

The analogy of this phenomenon to the operation of a radio vacuum tube can be made clearer by studying the mutual effects of a highly heated filament and an enclosing cylindrical electrode made preferably of a metal which is a good conductor of electricity. The filament may, of course, be conveniently heated to incandescence by passing an electric current through it. Now, if this filament and the surrounding cylindrical electrode are in a glass tube or similar container in which a *high vacuum* is maintained, and provision is made by the use of suitable connections to apply to the electrode a high *positive* potential, the electrode will be heated moderately merely by the "bombarding" action of the negative ions or *electrons* emitted from the incandescent filament. A glass

[1] DuFay, "Memoires de l'Academie," 1733.

[2] *Ions* are small charges of electricity which, according to our modern theories, are not supposed to be associated directly with matter. Negatively charged ions of electricity are called *electrons*.

tube containing a filament and an electrode in a rarefied atmosphere, as described, is called a *two-element vacuum tube.*

Reasons for the Use of Vacuum in Radio Vacuum Tubes.—The mutual action of a highly heated filament and a nearby positively charged electrode for producing electron emission is increased if the filament and electrode are in an enclosure from which the air and all other gases have been removed. The reason for this is that a gaseous atmosphere in the enclosure has a retarding influence on the emission of negative ions or electrons. Also, any effects due to the ionization of the gas by impact with the electrons are avoided.

Sometime before 1890, when Edison was engaged in experimental work with carbon incandescent lamps, he observed, when a metal plate was sealed inside a lamp bulb so that it was between and separated the two sides of the carbon filament but was entirely insulated electrically from the filament itself, that a current of electricity flowed through a galvanometer when connected between the outside terminal of the metal plate and the *positive* terminal of the filament. On the other hand, when the connection was reversed, that is, when the galvanometer was connected between the *negative* terminal of the filament and the outside terminal of the plate, no current flowed through the galvanometer. At the time Edison made this experiment, there was no satisfactory explanation. It is now known, however, that this action is due to the flow of electrons from the heated filament to the plate inside the bulb when the outside terminal of the plate is made positive. In other words, when the outside terminal of the plate is *positive* by being connected electrically to the positive terminal of a source of electricity, the electrons which are evaporated from the heated filament are *attracted* to the plate and set up a flow of current. When, however, the insulated plate is connected to the negative end of the filament, it is made *negative* so that it *repels* the electrons which are being evaporated, and consequently there is no noticeable flow of current from the filament to the plate. There is no perceptible flow of electrons in the latter case because they cannot leave the insulated plate to

flow to the filament, it being possible for only very small numbers of ions to escape from a cold body.

When stating the fact that ions can freely leave the surface of a hot body but cannot leave the surface of a cold body to an appreciable extent, the word "cold" is taken to mean that the temperature of the body is below that corresponding to a dull red heat.

When, therefore, an alternating current is applied to a heated filament surrounded by an electrode, both being in a rarefied atmosphere, it will be found that a current of electricity will flow in only one direction; that is, from the electrode to the hot filament.

Two-element Vacuum Tubes for Rectifying Alternating Currents.—Practical application can be made of this phenomenon for the rectification of alternating current, and vacuum tubes made especially for this kind of service are called *rectifying tubes.* When used for this purpose, one terminal from the alternating current supply is connected to either of the lead-wires supplying current required for heating the filament and the other terminal of the alternating current supply is connected electrically to the electrode surrounding the filament.[1]

An arrangement of a filament and an insulated plate with galvanometer and battery connections is shown in Fig. 1. A so-called "A" battery is used to heat the filament to incandescence. As shown in the figure, a "B" battery is in series with the negative terminal of the heated filament, the galvanometer, and the insulated plate. This is the condition when, as described before, the negative terminal of the filament

[1] At the moment when the field, due to the alternating current, acts in such a direction that the surrounding electrode is negative with reference to the hot filament, only positive ions can pass across, and the number of these is very small. On the other hand, when the alternating current reverses and produces a field in the other direction, there is a relatively free passage of electrons (negative ions) from the hot filament to the electrode.

The emission of negative electrons, unlike the positive ones, is quite steady, and is characteristic of the material of the filament and its temperature.

is connected through the galvanometer to the cold plate. Now, when the plate is made positive with respect to the heated filament, the electrons evaporating from the filament will be attracted to the plate, entering the plate and flowing back to the negative terminal of the filament through the wires connecting the galvanometer and battery. The electrons will then pass from the negative terminal of the filament to the side connected to the positive terminal and again evaporate on that side and pass on by attraction to the cold plate. On the other hand, when the conditions shown in the figure are reversed so that the plate becomes negative with respect to the

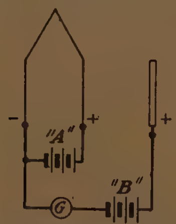


Fig. 1.—Circuit diagram in vacuum tube when the plate is positive.

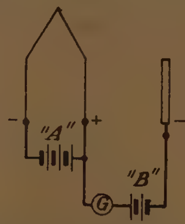


Fig. 2.—Circuit diagram in vacuum tube when the plate is negative.

filament, as in Fig. 2, the electrons coming from the filament will be repelled by the plate and will reenter the filament. In this case, there is no current in the plate circuit. The two-electrode vacuum tube may, therefore, be used as a rectifier of alternating electric currents as it permits the flow of current in only one direction. In this respect, this kind of vacuum tube has similar characteristics to some mineral rectifiers of radio currents called "crystal detectors." In fact, in the early years of radio communication, two-electrode vacuum tubes were used to some extent in the place of crystals. It was in 1905 that Prof. J. A. Fleming suggested the use of a two-electrode vacuum tube as a rectifier for the detection of radio waves, while in 1907 deForest conceived the idea of introducing a third electrode into a tube of this kind from which practically all the air and gases had been removed. This third electrode was in the form of a metallic mesh through which the electrons must pass on their way from the filament to the surrounding

electrode, which will now be called the *plate*. This original three-electrode vacuum tube, as first devised by deForest, is shown in Fig. 3. Because of its shape and appearance, deForest called this third electrode a *grid*, and he discovered that it served a very useful purpose in a vacuum tube, as it was a means of controlling the flow of electrons from the filament to the plate. The introduction of this grid into the vacuum tube made it possible to increase enormously the sensitiveness of the receiving apparatus used in radio work. By making the grid of a vacuum tube positive or negative, according to requirements, the amount of *current* flowing between the plate and the hot filament can be increased or decreased, as may be necessary. The grid in performing this function consumes practically no power for itself, serving merely as a sort of valve for controlling the amount of plate current.

FIG. 3.—Three-element vacuum tube as constructed by deForest.

Since the grid in a vacuum tube is nearer the filament than the plate, any change of potential difference between it and the filament produces a greater change of field strength at the filament than when there is an equal change of the potential difference between the plate and the filament. Thus, a relatively small change of the potential difference between the grid and the filament causes a relatively large change of the current flowing between the plate and the filament. As the electrons constituting this current from the plate to the filament come near the wires of the grid, they are attracted both by the grid when it is *positive with respect to the filament* and *by the positively charged plate.* In this case, the attraction of the *strongly positive plate tends to predominate*, with the result that relatively few of the electrons actually reach the grid; conse-

quently, nearly all are in the flow of electrons to the plate. On the other hand, in those cases which occur so frequently in practice, where the grid is *negative with respect to the filament*, the amount of current reaching the grid is so small that it may be considered a negligible quantity. Further, the action of the negative grid is to decrease the flow of electrons to the plate.

It will thus be seen that the grid provides a means of controlling the amount of current flowing from the filament to the plate, and that this control is obtained by the use of a small amount of current, and, also, by the expenditure of very little power (watts) for the reason that the voltage changes are very small.

Three-element Vacuum Tubes.—In this description of the action of vacuum tubes with three elements, that is, the filament, the plate, and the grid, it has been assumed in all cases that the atmosphere in the tube was very much rarefied and that, therefore, the gas, from whatever source, remaining in the tube had no effect on its action. In the so-called "hard" vacuum tubes, so little gas is present that this assumption is justified. A few types of vacuum tubes, however, usually called "soft" or gas tubes, contain a small amount of gas which was put into them during the process of manufacture. In the normal operation of these "soft" vacuum tubes, the stream of flying electrons from the heated filament to the positively charged plate has the effect of ionizing the gas contained in the tube and segregating from the gas some positive ions. These segregated positive ions, owing to their weight, move toward the filament quite slowly. In the space near the filament, these positive ions from the gas neutralize the negative electrons, which are farther away from the filament, thus permitting a greater current to be maintained with a given voltage difference between the filament and the plate than is possible in a so-called "hard" tube where there are practically no positive ions present from gases in the tube.

The materials commonly used at present for making the filaments of vacuum tubes will be discussed in later sections. The electrodes, both the plate and the grid, are usually made

of nickel or molybdenum or other conductors of electricity having high melting points.

The early three-element vacuum tube as constructed by deForest was called an "*audion*" and proved to be a very sensitive detector of radio currents, but was rather erratic in its behavior, the difficulty being that the various gases remaining in the tube after the imperfect and incomplete removal of gases, as attempted at that time, left so much residue that the ionization of the gases was a variable and, consequently, troublesome factor.

In 1912, improved methods were developed for the manufacture of radio vacuum tubes of the three-element type, making possible the almost complete removal of all the air and other gases in the tube to suit the special requirements of any kind of work, including the removal of the gases which had been absorbed in the metal of the electrodes and in the glass walls of the tube. Following these improvements in manufacture, vacuum tubes became dependable and reproduceable in their characteristics, so that it is now possible to calculate the proper proportions of a vacuum tube.

"Soft" tubes require more careful adjustment than "hard" tubes in order to obtain good results, but, when the proper conditions have been reached, they are more sensitive for detectors than the highly evacuated "hard" tubes. It should be kept in mind, however, that the vacuum tubes having the highest vacuum which is commercially obtainable contain some gases, there being, under the very best conditions, on the average, about one hundred million molecules of gas per cubic centimeter.

Briefly, the principle of operation of a three-element vacuum tube is that the flow of electrons from the hot filament to the cold plate is varied by applying variations of voltage to the grid. The circuit in the tube consists, therefore, of two branches: (1) the *output circuit*, or plate circuit, connecting the filament to the plate, and (2) the *input circuit* connecting the filament to the grid through the secondary winding of a transformer or other means of supplying variations of potential to the grid.

Since small variations in the potential applied to the grid produce large variations in the plate current, it can reasonably be expected that more power is released in the *output or plate circuit* than is expended in the *input circuit*, and this is actually the case. Since the power in the output circuit of the three-element tube is greater than the power expended in the input, it is possible to increase the degree of amplification by *feeding back*[1] part of the energy in the output to the input. If the proportion of the energy thus returned to the input circuit is large enough and the phase relations of the currents in the output and input circuits are right, the tube can be made to produce sustained oscillations.

The addition of the grid as a part of the radio vacuum tube produced a device of enormous possibilities, giving the vacuum tube the same importance as the steam turbine, the Diesel engine, the dynamo, and the telephone.

[1] Moyer and Wostrel, "Practical Radio," 3rd Ed., p. 67.

CHAPTER II

CONSTRUCTION OF VACUUM TUBES

The number of electrons emitted from a hot metal depends upon the kind of material and its temperature. Tungsten emits electrons freely and can be heated to high temperatures. This metal is, therefore, suitable for use in making the filaments in many types of vacuum tubes. The emission of electrons from platinum is not free but is increased considerably, even at low temperatures, if the platinum is coated with certain oxides such as those of strontium, barium, and calcium. A filament made of tungsten and thorium oxide also emits electrons freely.

Oxide-coated Tube Filaments.—An ordinary oxide-coated filament is made of a thin strip of nickel-platinum alloy for the filament with a *surface layer* of strontium and barium oxides. Compared with a filament made entirely of tungsten, one of the oxide-coated kind has a longer life and is capable of a given rate of electron emission at about one-tenth the filament power (watts) that is required by a tungsten filament. The end of the normal life of this type of filament is indicated by an actual failure or burn-out and not by a previous marked decrease in filament emission. The resistance of the oxide-coated type of filament is constant throughout its life because the current flows mostly in the core and the evaporation takes place from the coating. The approach of the end of life of such a tube is accompanied by an increase in temperature in places on the filament, sometimes indicated by "bright spots."

Thoriated Tungsten Filaments.—The type of filament which is made mainly of tungsten but contains a small percentage of thorium oxide is called a *thoriated tungsten filament.* In the process of manufacture the oxide is dissolved in molten tungsten before it is drawn into thread-like filaments. When a

filament of this kind is heated in the normal operation of a vacuum tube, part of the thorium oxide is changed to metallic thorium which accumulates on the outside of the filament and constitutes the active surface from which the emission of electrons takes place. At the specified temperature of operation, the emission of electrons from the filament surface takes place at the same rate as the thorium emerges from the interior of the filament. This process continues throughout the life of the tube provided the temperature of the filament is not excessively high. If, however, the temperature of the filament is raised a few hundred degrees Fahrenheit above the normal value, that is, to a temperature corresponding to a voltage overload of about 10 per cent of the rated value, the balance between surface evaporation of the thorium oxide and the supply of this oxide from the interior of the filament is disturbed. After being subjected for a time to this excessive voltage, the active thorium layer on the filament is completely evaporated, leaving a clean tungsten surface. The filament emission then decreases rapidly because the electron emission of a tungsten filament even at this excessive temperature of operation of the thoriated tungsten filament is very small. Because of the increase in temperature, however, the rate of formation of the metal thorium from its oxide is increased, but the rate of surface evaporation is increased to a greater degree. If the filament voltage is still further increased, the overload on the tube is increased until finally no emission at all is obtained. Under certain conditions, ionization[1] of the gas in a tube will serve to dissipate the thorium on the filament or to neutralize its activity. On the other hand, if the temperature of operation is *below* the normal value (corresponding to an underload) the rate at which the surface layer of thorium is retained may be likewise retarded, with the result that the filament may be "paralyzed." The normal life of a thoriated tungsten filament ends when the thorium supply is exhausted. The indication of the exhaustion of the thorium is a sudden decrease in filament emission, and not an actual failure or burn-out as in the oxide-coated filaments.

[1] Ionization of the gas is explained on p. 17.

Pure Tungsten Filaments.—The pure tungsten filament has now been replaced by the more efficient oxide-coated and thoriated filaments. Pure tungsten filaments were used in the so-called "type UX-200" and "201" vacuum tubes which are no longer manufactured.

Filament Emission.—The available supply of electrons at the filament must always be greater than the "demand" produced by the plate current. Thus, the normal maximum plate current of a so-called "type UX-171" three-element vacuum tube is 20 milliamperes. But at the full output of the tube the plate current varies from about 1 to about 40 milliamperes. Consequently, in order that the "peak" current may be "handled" by the tube without distortion, the minimum satisfactory electron emission for this type of vacuum tube is about 50 milliamperes.

Comparison of Tungsten, Thoriated Tungsten, and Oxide-coated Filaments.—For a given emission the filament power (watts) required by a tungsten filament is about four times as great as required for a thoriated tungsten filament and about ten times as much as for one coated with oxide. Thus, the oxide-coated filament requires less than half as much filament power as the thoriated kind for the same emission.

While the oxide-coated and thoriated kinds differ in the character of emitting surface, operating temperature, and capacity for overload, their efficiency is about the same. In other words, filaments of both kinds having similar ratings and service capacities have, approximately, the same total emission currents for a given amount of power. The relative efficiencies of thoriated tungsten and pure tungsten filaments can be shown by a comparison of the filament power requirements for the UX-201 and 201A types of tubes. The UX-201 type requires 5 watts of power with a filament current of 1 ampere at 5 volts. The UX-201A type requires only one-quarter as much, or 1.25 watts, with a filament current of 0.25 ampere at 5 volts. Furthermore, the average emission of the filament of a UX-201A type is 45 milliamperes, which is 7.5 times that of the UX-201 type. On the basis of equal power input, the emission of the UX-201A type is about twice

that of the UX-201 type. Another example of the advantages of the thoriated filament is shown in the UX-199 type, which has about the same emission and somewhat better operating characteristics than the UX-201 type, but its filament requirement in watts is only one-twenty-seventh as much.

The surface layer of thorium in the thoriated tungsten filament is thinned out by operation at a too high temperature or may even be dislodged by the impact of positive gas ions due to ionization of the gas in the bulb. This filament may, however, be reactivated.[1] The thoriated tungsten filament is more uniform than other filaments in its characteristics partly because the manufacturing process in making it is less complicated. Also, a high degree of vacuum can be obtained in tubes using this type of filament. Thus an oxide-coated filament is more subject to the injurious effect of ionization of gas in the tube than one of the thoriated-tungsten kind. Recent improvements in the manufacture of the oxide-coated filament tend to give it a considerably increased life.

At the rated operating temperature, the oxide-coated filament is dull red in appearance, the thoriated filament is yellowish, and the pure tungsten filament is whitish.

Manufacture of Vacuum Tubes.—A step-by-step description of the assembly of the parts of a vacuum tube will serve to illustrate its construction. Figure 4 shows the glass tube T which serves as the main support of the elements of a vacuum tube and Fig. 5 the kind of construction which is used to hold the supporting posts R and the lead-in wires W in the glass seal S. This glass seal is fused to the top of the flanged glass tube T, and a long piece of thin glass tubing E is fused into the side of the glass tube T, as shown in Fig. 6. At the stage in manufacturing shown by these figures, both ends of the glass tube E are open because during the fusing process air is blown through the tube. The progress of construction after the supporting posts R are bent to the proper position is illustrated in Fig. 7. The type of filament F

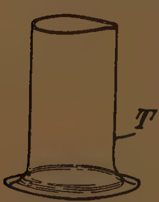


Fig. 4.—Glass support for vacuum tube.

[1] Reactivation or rejuvenation of vacuum tubes is explained on p. 79.

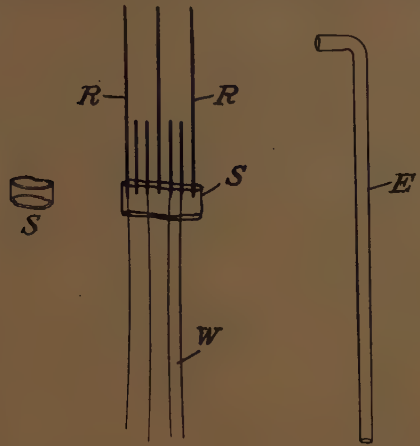


FIG. 5.—Method of attachment of supporting posts and lead-in wires.

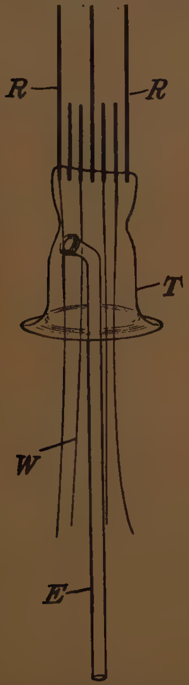


FIG. 6.—Method of attaching glass tube used for evacuating air.

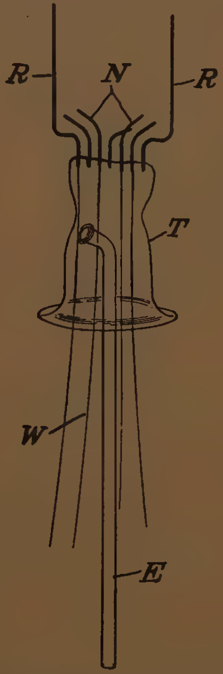


FIG. 7.—Position of supporting posts for attachment of filament, grid and plate.

in Fig. 8*a* is welded, in the next stage of assembling the parts, to the supporting posts *N* of Fig. 7.

One type of grid *G* is shown in Fig. 8*b* where the grid wires are welded to a suitable frame. Another method is to press the grid wires into the soft metal of the frame during the process of winding. A very fine tungsten wire is used for making the grid. This drawing shows, also, one form of

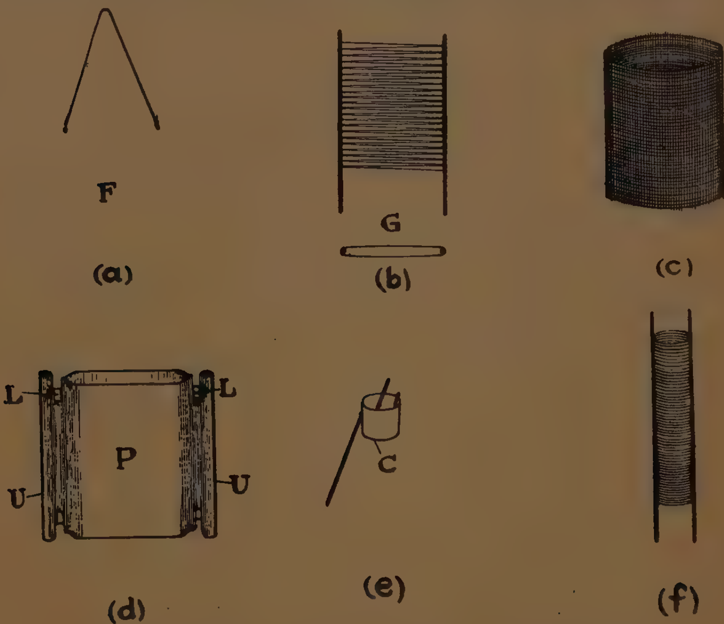


FIG. 8.—Details of construction of filament, grid and plate.

circular *grid* Fig. 8*c* used in type UX-222 vacuum tube, and in Fig. 8*d* a plate *P* consisting of two pieces which are held together by the small lugs *L*. The tubes *U* thus formed at each side of the *plate P* slide over the supporting posts *R*. In some types of tubes this plate is sand-blasted to give it a better heat radiating surface.

Various forms of plates are used, from the wire-wound type to heavy sheet metal. The material is usually nickel, molybdenum, or tungsten. The "*getter*," the action of which is

described later, is contained in the receptacle C as in Fig. 8e, or, in some forms of construction, is fastened directly to the plate P.

Figure 9 shows the assembly of the elements of a standard type of vacuum tube. The ends of the filament F are welded

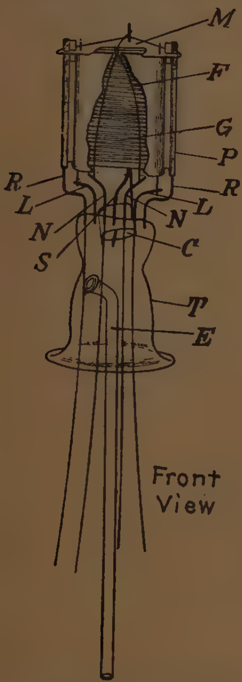


FIG. 9.—Assembled elements of standard vacuum tube.

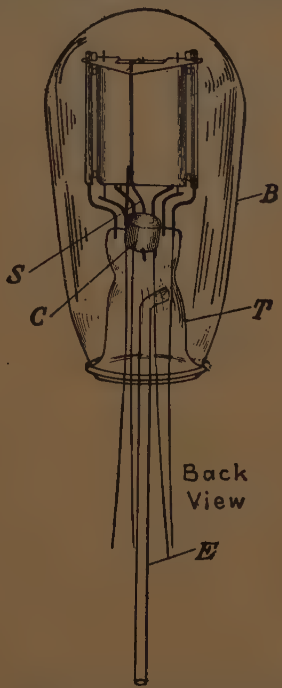


FIG. 10.—Elements of vacuum tube when covered with glass bulb.

to their supporting posts N, the frame of the grid G and the side tubes U of the plate P are welded to posts L and R respectively, and the "getter cup" C is welded to post S.

In some types of vacuum tubes the filament may be mounted in such a way that it is held under tension by a spring. Finally, some form of insulating support, in this case a mica strip M, is fastened at the top of the assembly to keep the elements in alignment and to provide rigidity. A glass bulb B is placed over the unit as indicated in Fig. 10 and fused to

the flange on the large glass tube *T*. The only connection between the inside of the bulb and the atmosphere is through the very small glass tube *E*.

Many of the glass-sealing processes used in the manufacture of vacuum tubes require careful annealing of the glass parts of the tube. This is accomplished by allowing the temperature to drop very slowly. Molten glass which is cooled quickly is subject to internal strains. When the cooling is rapid, the temperature at the surface drops quickly and the outside layer solidifies. The interior, however, tends to contract and exert an inward pressure on the outer layer. This may result in cracks.

The air and other gases are exhausted from the glass bulb of the tube through the small glass tube *E*.

Care is required to get rid of all the air and other gases, not only in the space inside the glass bulb, but, also, in the walls of the bulb and glass tubes and in the metal of the elements. Even if a bulb is thoroughly exhausted by a vacuum pump, it subsequently would give indications of the gases which gradually come out of the interior parts. At ordinary temperatures, these gases are released so slowly that the period of evacuation would have to be lengthened to a prohibitive extent before the vacuum is satisfactory. In order to drive out quickly these gases from the walls of the bulb and the elements, the tube is kept hot during the process of exhaustion. For a similar purpose, the filament may be heated by electric current and a positive voltage applied to the grid and plate so that they are heated by the impact of electrons from the filament. The evacuation is continued until the vacuum reaches a value corresponding to a pressure of a few hundred thousandths of a millimeter of mercury. When the desired degree of vacuum is obtained, the small glass tube *E* is melted off and the bulb is thus permanently sealed.

The baking or heating temperature in the tube when air and other gases are being removed is considerable greater than that of normal operation of the tube in service. The tungsten tube can withstand a higher baking temperature than either the thoriated-tungsten or the oxide-coated kinds. Hence the

degree of vacuum which may be obtained in these vacuum tubes is somewhat limited, particularly in those with oxide-coated filaments, which become impaired quickly when overheated.

During the operation of a vacuum tube in service a further release of gases takes place. To absorb these gases a small supply of a so-called "getter" is assembled with the tube elements. This consists of an alkali metal such as magnesium or such substances as phosphorus, arsenic, and sulphur, which volatilize readily. When the tube is sealed this "getter" is volatilized and then condenses in a silvery film on the inside of the glass bulb. This film not only attracts the gases as they are released but also tends to seal the gases in the walls of the bulb.

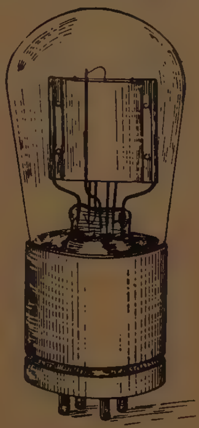


FIG. 11.—Vacuum tube showing contact prongs.

Finally, the glass bulb is cemented to a suitable insulating base in the bottom of which are 4 small hollow rods. The lead-in wires pass through these rods and are fastened to them by a drop of solder at the bottom of each rod. These rods form the contact prongs of the vacuum tube which is then made up as shown in Fig. 11. The vacuum tube next undergoes a number of tests which are described elsewhere, and, if satisfactory, is ready for use.

Ionization by Collision.—It is impossible to remove completely all traces of gas from a vacuum tube. In a rarefied gas some of the electrons are parts of atoms and some are free. These free electrons move with such velocity that if one hits an atom another electron may be knocked off. This "stray" electron comes under the influence of the plate voltage and moves in the same direction as the colliding electron, that is, toward the plate in the vacuum tube. The remainder of the atom, which is a positively charged *ion*, moves in an opposite direction toward the filament. Thus, both parts of the atom act to increase the flow of current through the gas. This

action of an electron on an atom is called *ionization by collision* and corresponds to the "break-down" of any electric insulator at excessive voltage. In a vacuum tube which contains residual gas, some ionization will occur when the plate voltage exceeds 30 or 40 volts, although vacuum tubes having a high vacuum may not have their operation appreciably affected by ionization.

Influence of Gas in a Vacuum Tube.—The relation between plate current and plate voltage for operation at rated filament voltage in a vacuum tube having no gas is shown by the curve

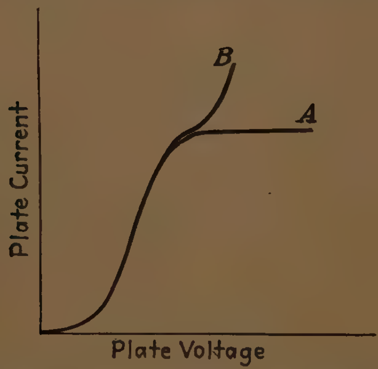


FIG. 12.—Curve showing relation between plate current and plate voltage with and without gas ionization.

A in Fig. 12. Under the action of ionization by collision the gas atoms are separated into free electrons and positively charged ions which move toward the plate and filament, respectively. This movement produces an increase of current as shown by curve *B*. It may be considered that ionization of the gas tends to neutralize the space charge and thus permits a larger current to pass through the tube.

There seems to be an apparent advantage in ionization by collision because the plate current is increased; but it happens that under this condition the filament deteriorates rapidly because the positively charged ions are attracted forcibly to the negatively charged filament, and, since they are much heavier than electrons, the impact breaks down the filament

surface. Also, if a too high plate voltage is applied, a "blue-glow" discharge may result. In this condition, a tube is erratic in behavior and becomes insensitive because the plate current is so large that it is not affected by variations of the grid voltage. If a tube has a "blue-glow" discharge, its characteristic curves do not repeat themselves and sharp breaks in the curves may appear. Further, such operation heats the tube elements and such heating may injure them.

Ionization in a Detector Tube.—To a certain extent ionization in a vacuum tube is of value in its use as a *detector*. "Soft" tubes are particularly useful as detectors and, if properly selected and operated, may be more satisfactory as detectors than "hard" tubes of similar construction. They are, however, quite critical of adjustment because the plate or grid voltage must be adjusted to a value just under that which produces ionization. The high-vacuum detector tubes used at the present time are less sensitive but much more dependable than the older tubes which did not have such good vacuums.

Ionization seldom takes place in a tube using the tungsten filament because the vacuum is high. It is more likely to occur in tubes using oxide-coated filaments because of the presence of occluded gas. A power tube[1] with an oxide-coated filament when once ionized cannot be used again at the usual high plate voltages unless it is reexhausted. It may, however, serve for use at lower plate voltages.

The rectifying property of a two-element tube is ineffective if the plate becomes heated to incandescence. This heating takes place when an excessively high plate voltage is applied. The high voltage increases the velocity of the electrons which heat the plate by the force with which the electrons impinge on it.

Testing a Vacuum Tube for Presence of Gas.—No considerable number of electrons will be given off from a *cold* element in a tube unless it is subjected to a strong electron bombardment. If, then, there is current flow in a tube in a

[1] A power tube is a vacuum tube intended for the "last" audio-frequency stage of a receiving set. It takes its name from the fact that its power rating in watts is greater than for the usual types of tubes.

direction which shows that electrons are emitted from a cold element, either the grid or the plate, it is proof of the presence of gas which is conducting the current.

One method of ascertaining the presence of gas in a tube is to apply the so-called *overvoltage test*. This consists of applying a plate voltage, higher than the normal operating value, for a few minutes and then testing the tube for performance. During the application of this excess voltage, some gas is released from the elements of a vacuum tube in which the vacuum is poor. If the tube performance is satisfactory, the amount of gas released is not enough to impair its action.

If a negative voltage is put on the grid of a vacuum tube in which there is no gas, the grid current does not reverse. It is found, however, that even in a tube having a high vacuum there is enough gas left so that the positive ions produce a minute reversed grid current when the grid is negative. The strength of this grid current increases with the strength of the plate current. This action in the flow of grid current can be made to serve as a test of the amount of gas present in a tube.

The presence of a large amount of gas in a tube may be detected during the final stages of manufacture by a simple test utilizing a source of high-frequency voltage which may be impressed across the tube elements. The color and distribution of the arc across the tube elements indicates the condition of the vacuum.

Relation between Tube Constants and Structure.—The two main factors that enter into the design of vacuum tubes are the amplification factor (see page 69) and the plate resistance. The *amplification factor* u increases with increasing distance between the plate and the grid and depends, also, upon the spacing and size of the grid wires but not upon the distance between the filament and the grid. In practice it is found that u is not quite constant but decreases slightly at low voltages, although the variation is not appreciable within the operating range.

The *plate resistance* r_p is inversely proportional to the surface areas of the plate and filament. It depends, also, upon the operating voltages. The value of r_p is further affected by u

which, as shown above, depends almost entirely upon the structure of the grid and its position with relation to the plate.

An amplifying tube gives best operation when its *plate resistance* is equal to the *impedance* into which the tube works. In cases where this is not possible the total plate resistance may be reduced by operating the vacuum tubes in parallel; or, by the use of an *output transformer*, the plate resistance of a tube may be matched to the impedance of the device into which it works.

The mutual conductance G_m, being equal to u/r_p depends upon the factors which determine these terms. In some types of tubes it is necessary to make this ratio u/r_p as large as possible. Then, for a given value of u, r_p must be as small as possible. To make u large and r_p small, therefore, the grid must be close to the filament.

When a vacuum tube is to be used as a detector, it should have a low internal resistance which changes suddenly within narrow limits when the grid voltage is varied. Since the amplification factor depends on the ratio of the change in the plate voltage to the change in the grid voltage, the maximum action is obtained when, for a given change of the grid voltage, the necessary change of the plate voltage to provide the same current is a maximum. Thus, in a detector tube the resistance must drop suddenly from a maximum to a minimum for a small change in grid voltage. In an amplifying tube, on the other hand, a small change in grid voltage should tend to increase the resistance to a maximum. The nearer the grid is to the filament and the farther the grid is from the plate, the better are the detecting qualities of a tube. Conversely, the farther the grid is from the filament and the closer the grid is to the plate, the better are the amplifying qualities of a tube.

Limiting Operating Conditions.—Since some gas always remains in a vacuum tube, there are in every tube a large number of molecules of gas left even when the vacuum in the tube is as high as possible. Ionization of this gas will occur if the plate voltage applied to the tube is too high, or if both the filament voltage and plate voltage are high. The extent of the effect of ionization on the tube characteristics depends upon

the amount of gas present. Thus, one limiting condition of the operation of a tube at high voltages is due to ionization of the gases left in the tube. Tubes using oxide-coated filaments cannot be so completely evacuated as those having filaments consisting only of tungsten, hence ionization is more likely to occur in the former.

The other limiting condition is the deterioration of the elements of a vacuum tube from overheating. Thus, the heating of the plate is due to electron bombardment, the amount of power taken by this heating being the product of plate current and plate voltage. The electrons moving from the filament to the plate convert this power first into an increase in their velocity and then into heat which is released when they reach the plate. This heat, since the elements are in a vacuum, can be dissipated only by radiation. It may be mentioned here, again, that a tube may cease to function if its emission is impaired by the impact of positive ions on the surface of the filament.

The plate may get so hot that the glass bulb will give way by sagging. In high-power tubes this difficulty is avoided by changing the construction so that the outside of the tube comprises the plate. Then cooling water can be circulated around the plate to carry off the heat. The plates of high-power air-cooled tubes are sometimes blackened to increase their heat radiating capacity. Sand-blasting or even oxidizing the plates of low-power tubes produces somewhat the same effect.

The factor of *distortion* has a bearing on the possible output of a vacuum tube. Several operating conditions must be assumed if the distortion is to be below the value which is considered to be a minimum. The table on page 196 states these operating conditions and gives the maximum undistorted outputs of a number of tubes.

Life of a Tube Filament.—The life of a filament is shortened by excessive heating due to impact by positive ions produced by collision due to ionization, which occurs to some extent even in tubes having a high vacuum. The normal life of a filament depends, also, upon the rate at which the substance

volatilizes. As a metallic filament, for example, one of tungsten, volatilizes, its resistance increases. This causes a decrease in filament current, if operation is at constant voltage, and hence a decrease in electron emission. On the other hand, if the operation of the tube is with a constant current, the voltage is increased, and the filament temperature rises. The effect of this is to shorten the life of the filament.

In an oxide-coated filament only the surface volatilizes. The filament current flows mainly through the core, the resistance of which remains constant. With this kind of filament the impact of positive ions produces local heating which is cumulative and tends to burn out the filament at that place.

CHAPTER III

FUNDAMENTAL ELECTRICAL RELATIONS

It is well known that many common forms of matter can be made to show evidences of the phenomenon which we call "electricity." Thus, if a piece of hard wax is rubbed with a cloth which is then taken away, both bodies will attract light bits of paper. The wax is said to have a negative charge and the cloth a positive charge. It can be shown also that "like" charges repeal each other while "unlike" charges attract. When equal "unlike" charges come into contact they combine and a neutral state results.

Electrostatic Field.—This mutual effect of one charge upon another exists even when there is a considerable distance between them. The space around the charged bodies is said to be under a strain which allows it to act upon another charged body. This space is called an "electrostatic field" which extends in all directions around a charged body. At any considerable distance from the body, however, the field intensity or strength is small because it varies inversely as the square of the distance from the body.

Electrons.—Every substance consists of a large number of atoms and molecules, which, for a given substance, are alike. In order to account for the presence and behavior of electricity in matter, it is considered that the atom has a charge of positive electricity and that a number of charges of negative electricity rotate at great speeds around this center. Normally, the sum of the negative charges balances the positive charge. These negative charges, which are all equal, are called *electrons* and represent the smallest amounts of electricity which can be conceived. The arrangement and number of these moving electrons belonging to an atom determine whether the atom is copper, or silver, or hydrogen, and so on.

For ease of calculation, the electron is assumed to be spherical in shape and to have a diameter of ⅕ of a trillionth (2×10^{-13}) centimeter. The average velocity of the electrons is about 100 kilometers per second at 0°C. An idea of the extremely small size of the electron may be obtained from the estimate that in a tiny spherical globule of copper having a diameter of 0.000,01 inch there are about twenty billion electrons. The atom formerly was regarded as the smallest particle of matter which could exist; something like 250,000 hydrogen atoms placed in a row would have a length of 0.000,01 inch. The weight of an electron is only about 1/2,000 of the weight of a hydrogen atom.

Some of the electrons, in moving about, may escape from one atom and get into the atomic system of another. If an atom loses an electron the *balance* between positive and negative charges is destroyed and the atom is left positively charged. In the same way, a *negatively charged* body is one which has obtained more than its normal number of electrons.

Electric Current.—These free atoms may be acted upon by an electric charge outside the body in such a way that they travel[1] in a common direction and constitute what is called an "electric current" in the body. Hence the *flow* of an electric current in a conductor is considered to consist of the *motion* of immense numbers of electrons. When the external distorting force is removed, the original condition of the structure of the atom is restored.

The intensity of this electric current, that is, the unit quantity of electricity flowing in a wire during a unit of time, is called an *ampere*. This intensity has the same value at all points along the circuit.

Direction of Flow of Current.—The flow of current has been defined *arbitrarily* as taking place from the positive to the negative end of a conductor; that is, in a wire connecting the terminals of a battery the direction of the flow of current is

[1] According to another theory, it is held that an electric current or the process of conduction is brought about by the spontaneous discharge of electrons from one molecule to another. The function of the electrostatic field here is to influence the direction of the discharge, which, in its absence, would be at random.

from the positive terminal of the battery to the negative. But it has been shown that electrons, being negative charges, move from negative to positive. Hence it must be remembered that the direction of electron flow is opposite to that of current flow as represented in Fig. 13.

The amount and rate of flow of electricity can be detected by the chemical, heating, and magnetic effects which it produces. A familiar example of chemical action is the process of electrolysis used in electrotyping, electroplating, and in the refining of metals. The heating effect of electricity depends upon the quantity of current flowing, and varies as the square of the current applied. In the incandescent lamp a filament is heated to incandescence by an electric current.

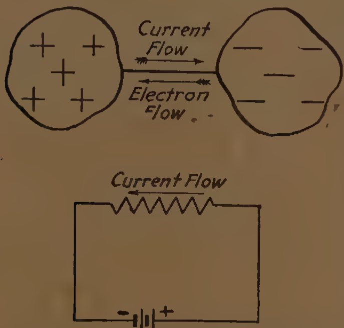


Fig. 13.—Electron flow opposite in direction to current flow.

The electrostatic field, which has already been described, is an effect of electricity at rest. Electricity flowing in a conductor sets up another kind of effect called a "magnetic strain" in the space surrounding the conductor. The space in which this field exists is called the "magnetic field." The magnetic field consists of imaginary lines of force which form closed circles around the conductor. The *direction* of the magnetic force may be indicated by its effect on a compass needle held near the conductor.

Conductors and Insulators.—Matter may be regarded as belonging to two classes, one of which possesses free electrons, and the other does not. A substance having free electrons is called a "conductor" and is said to offer a low resistance (or opposition) to the flow of an electric current. A substance which does not have free electrons is an insulator and offers a high resistance to the flow of electric current.

All substances, however, contain some free electrons and, theoretically, will allow the passage of an electric current

although the resistance of some may be so extremely high that the material is considered a good insulator. Further, the resistance of some materials is not constant; it may, for example, vary inversely as the temperature of the material. That is, the material may serve as an insulator at low temperatures and a conductor at high temperatures.

Examples of good conducting materials are the metals and that class of liquid conductors called the *electrolytes.* Examples of insulating materials are dry gases, glass, porcelain, hard rubber, and various waxes, resins, and oils. The minute current which can be forced through an insulator under certain conditions is called a "leakage current."

Difference of Potential.—If one piece of a substance is charged positively and a piece of another substance is charged negatively, there is said to be a *difference of potential* between them. When these pieces are connected by a wire, as in Fig. 13, there is a flow of current through the wire while electrons pass through the wire from the negatively charged piece to neutralize the positive charge on the other piece. The electric charges which accumulate at the ends of the wire have the effect of neutralizing the original conditions of charge.

If the original difference of potential is maintained by removing the neutralizing charges as they accumulate, the flow of the electric current will be steady and continuous. Such a steady difference of potential or *electromotive force* may be provided by putting the charged bodies and their connecting wire into a closed circuit containing a device capable of developing an electromotive force.

Electromotive force may be developed by friction, by thermal means, by chemical action, and by induction as in an electric generator. Electricity may be produced by *frictional machines* at high voltages but with very small amounts of current. This method of producing electromotive force is not practical because of the difficulties encountered in connection with insulation, dampness, and variation in performance.

Electromotive force may be produced by heating the junction (*thermocouple*) of two unlike metals. Tables of the thermo-electric power of metals are given in most electrical

handbooks. The electromotive force developed at a junction of steel and constantan wires is about 30 microvolts.[1] Low voltages but fairly large currents are possible.

The production of electromotive force by chemical action is exemplified by the *battery*. This action is due to the fact that a difference of potential exists between two different substances used in the battery, such as zinc and carbon when placed in certain chemical solutions. The efficiency of this method is high but the cost of producing electricity for most purposes is prohibitive because of the expense of the materials.

The ability of an electric generator to produce an electromotive force and thus maintain a difference of potential is due to the condition which results when the wires on the armature of the generator pass through the magnetic field of magnets, called *poles*.

Kinds of electromotive force may be classed as constant and alternating. A *constant electromotive force* does not change in direction of flow or in strength. An *alternating electromotive force* varies periodically in direction of flow and in strength.

Resistance.—As the free electrons move along a conductor it is supposed that they hit the atoms of the substance which lie in their paths. The effect of this opposition is to reduce the velocity of the electrons. The extent of the opposition is proportional to the electrical resistance of the conductor. Resistance varies with the shape, substance, and temperature of the conductor. The unit of resistance is called an *ohm*. For very small resistances the millionth part of an ohm is used as a unit and is called a *microhm*.[2] For high resistances a million ohms is used as a unit and is called a *megohm*.

Unit of Electromotive Force.—The unit of electromotive force or voltage is called a *volt*. One volt is that voltage which will force a current of 1 ampere through a resistance of 1 ohm.

Conductance.—A circuit which offers but little resistance R to a current is said to have good conductance. If conductance if represented by G then $G = 1/R$ or $R = 1/G$. The unit of conductance is called a *mho*.

[1] A microvolt is a millionth part of a volt.

[2] See Appendix for explanation and table of metric prefixes.

Resistance of a Wire.—If r is the *specific resistance* of a substance, that is, the resistance of a unit wire, then the resistance R of a conductor having a length of L feet, and a cross-sectional area of A circular mils (as defined below) is

$$R = \frac{rL}{A}.$$

A unit wire is a round wire 1 foot long and 1 mil in diameter (or having an end area of 1 circular mil). A *mil* is equal to 0.001 inch. The area of a wire 1 mil in diameter is 1 *circular mil.* The area of a circle in circular mils equals the square of the diameter in mils.

To find the resistance in ohms of a length of any size of wire, multiply the specific resistance, that is, the resistance in ohms of one *circular mil-foot,* by the length in feet and divide by the square of the mil diameter (circular-mil area). Tables of specific resistances and wire sizes in mils are given in the Appendix.

It is obvious that the resistance of a conductor varies directly with its length; that is, as length increases, the resistance increases. Also, the resistance varies inversely with the cross sectional area; that is, as the area increases, the resistance decreases.

Variation of Resistance with Temperature.—The variation of the resistance of a pure metal with changes in temperature is given by the equation,

$$R_t = R_o(1 + a \times t)$$

in which

R_t = resistance at t°C.
R_o = resistance at 0°C.
t = temperature at t°C.
a = temperature resistance coefficient.

If it is assumed that $a = 0.004$ the equation may be stated thus: for each 2.5°C. rise in temperature above 0°C. the resistance increases about 1 per cent.

The resistance of some substances does not follow this rule. Thus, carbon shows a decrease in resistance with increase in temperature; one alloy of nickel and copper shows no increase in resistance with ordinary increases in temperature.

Series and Parallel Circuits.—In radio work some units of apparatus are connected in series and others in parallel. If the various parts of a circuit are connected in such a way that the total current must flow through each part, the parts are said to be in *series*. If the analogy of the flow of electricity to the flow of water is used, this corresponds to the pipe line

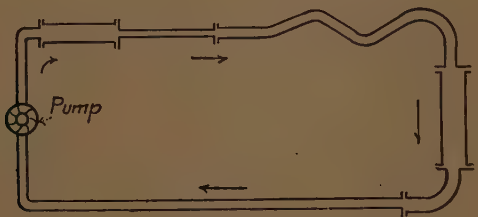


FIG. 14.—Water pipes connected in series.

shown in Fig. 14 in which pipes of various sizes and lengths are connected in series. If the various parts are connected in such a way that the total current is subdivided, the parts are said to be in *parallel*. The corresponding condition in the pipe line is shown in Fig. 15. If each of the four paths offers the same resistance to current flow, then the total current at A will be divided into four equal parts, which unite again at B. The equivalent resistance R of a group of resistances r_1, r_2, r_3, r_4, and so on *connected in series* is equal to the sum of the separate resistances; that is $R = r_1 + r_2 + r_3 + r_4 + \cdots$ The equivalent resistance R of a group of resistances r_1, r_2, r_3, r_4, and so on, *connected in parallel*, is equal to the reciprocal of the sum of the reciprocals of the separate resistances. That is,

FIG. 15.—Water pipes connected in parallel.

$$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_4}}$$

Relation between Current, Voltage, and Resistance.—The opposition offered by the resistance R of a conductor to the

flow of current reduces the effective velocity of the electrons and hence decreases the strength of current I. In order to compensate for this opposition, and, thus, to maintain a constant value of current flow, it is necessary to apply to the circuit an electromotive force or voltage E which is equal to RI. If R is the resistance in ohms and I is the current in amperes, then E is in volts. This relation is known as *Ohm's law* and may be expressed in the three forms below:

$$E = IR, \text{ or voltage} = \text{current} \times \text{resistance, or volts} = \text{amperes} \times \text{ohms.} \quad (1)$$

$$I = \frac{E}{R}, \text{ or current} = \frac{\text{voltage}}{\text{resistance}}, \text{ or amperes} = \frac{\text{volts}}{\text{ohms}}. \quad (2)$$

$$R = \frac{E}{I}, \text{ or resistance} = \frac{\text{voltage}}{\text{current}}, \text{ or ohms} = \frac{\text{volts}}{\text{amperes}}. \quad (3)$$

Ohm's law holds true for any circuit or part of a circuit. When the equation is used for a *part* of a circuit the values of voltage, current, and resistance must apply to that part only.

Rheostats.—In radio work the need is constantly arising for adjusting a current to a specified value. This is usually done by varying the resistance of the circuit. Changes in the resistance of the circuit can be made by means of resistance devices called *resistors*, which are either variable or fixed in value. Variable resistors are called *rheostats*.

Size of Rheostat Required for Vacuum Tubes.—In deciding what size of rheostat to use, it is necessary to know the battery voltage and the current consumption. Thus in the case of a UX-201A tube which requires for the filament current 5 volts and 0.25 ampere, the amount of current is about as high as can be economically supplied by dry cells. Since each new dry cell has a voltage of 1.5, 4 cells connected in series as shown in Fig. 16 are needed. In a series connection the total voltage is always the sum of the individual voltages, and in this case is 6 volts.

Since only 5 volts are required and the dry-cell battery gives 6 volts, it is necessary to produce a voltage drop (loss of volts) of 6 minus 5, or 1 volt. Remembering that electrical resistance in ohms is equal to "voltage drop" divided by amperes,

then the required resistance of the rheostat is 1 volt divided by 0.25 ampere, or 4 ohms. Rheostats are commonly made in 6- to 30-ohm sizes, so that in the case above, the 6-ohm size will be sufficient. Figure 17 shows 2 cells connected in parallel. This arrangement might be used to light the filament of a

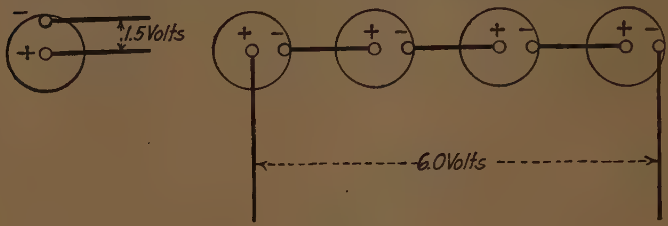


FIG. 16.—Dry cells connected in series.

WX-12 tube which requires 1.1 volts and 0.25 ampere. The total current would be divided by the parallel connections, so that in this case, each cell would give one-half of 0.25, or 0.125 ampere, and the life of the cell would, of course, be increased considerably. Here the size of the resistance required is equal to $\frac{1.5 - 1.1}{0.25}$, or 1.6 ohms, and a 6-ohm rheostat would be used.

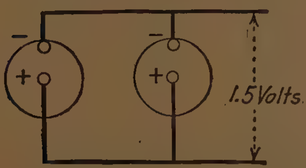


FIG. 17.—Dry cells connected in parallel.

Power and Energy.—The work accomplished by the voltage E in moving an electron through a unit length D is equal to DE (since work = force × distance through which it acts). A current I flowing in a conductor corresponds to a transfer of N electrons per second through a unit length D.

Power being defined as the rate at which work is done, the total work performed per second or the power is then $W = NDE$ or IE. The unit of power is called a *watt.* A watt is the power expended by a current of 1 ampere flowing through a resistance of 1 ohm. One *kilowatt* is equal to 1,000 watts.

Since $E = IR$ then by substitution $W = I^2R$.

and since $I = \frac{E}{R}$ by similar substitution $W = \frac{E^2}{R}$.

Thus there are three forms of the equation for power W,

$W = EI$, or power = voltage $\times$ current, or watts = volts $\times$ amperes. (1)

$$I = \frac{W}{E}, \text{ or current} = \frac{\text{power}}{\text{voltage}}, \text{ or amperes} = \frac{\text{watts}}{\text{volts}}. \quad (2)$$

$$E = \frac{W}{I}, \text{ or voltage} = \frac{\text{power}}{\text{current}}, \text{ or volts} = \frac{\text{watts}}{\text{amperes}}. \quad (3)$$

Each of the expressions $W = I^2R$ and $W = E^2/R$ can be stated in three forms in a similar manner.

Energy is expressed in the same units as work. The commercial unit of electrical energy is the *kilowatt-hour*. Electrical energy is measured by an instrument called the integrating *wattmeter* which automatically adds up the work done, though there may be a continual variation of power.

The energy which is required to maintain the velocity of the electrons is given up by them in the form of heat caused by their collisions with each other and with the atoms.

Applications of Ohm's Law and Power Relations.—It is a simple matter to carry out the calculations for the action of a direct-current circuit. Thus, to determine the resistance of the filament of a UX-201A tube it is necessary only to apply the relation $R = E/I$ or ohms = volts/amperes. A UX-201A tube takes 0.25 ampere at 5 volts. Hence the resistance equals $5/0.25$ or 20 ohms. The conductance being the reciprocal of resistance is equal to $1/20$ or 0.05 mhos.

If a voltage of 45 volts is applied to the plate-to-filament circuit of a UX-201A tube, the plate current will be 0.0017 ampere. Then the internal or direct-current resistance R in ohms of the tube from plate-to-filament is $R = E/I =$ 45 volts/0.0017 amp. = 26,470 ohms.

The power input W in watts of the filament circuit is $W = EI$ = 5 volts $\times$ 0.25 ampere = 1.25 watts. The power output W of the plate circuit is $W = EI$ = 45 volts $\times$ 0.0017 ampere = 0.077 watt.

The electrical energy taken by a device rated at 80 watts over a period of 10 hours is 80 $\times$ 10 or 800 watt-hours, which is equivalent to 0.8 kilowatt-hour. At a cost of 10 cents a

kilowatt-hour the expense of operating the device is 0.8 × 10 or 8 cents.

Direct Current.—The electric current which is supplied by all kinds of batteries is *direct current*. That is, it flows in one direction through the circuit. In Fig. 18 for instance, if the pressure or voltage of the battery is steady, the current will be steady and will flow from the + terminal of the battery, through the circuit to the − terminal of the battery. If the voltage is pulsating, that is, if it rises and falls in strength, but acts in one direction only, then the current also rises and falls in strength and is called a *pulsating direct current*.

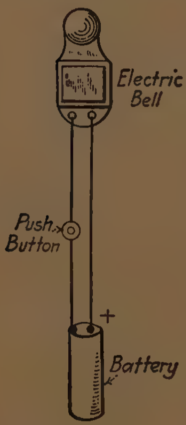


Fig. 18.—Electric bell operated by dry cell.

Alternating Current.—When radio waves are changed into an electric current by means of a radio receiving apparatus, this current, instead of flowing in one direction, not only changes its direction at a definite rate but also varies in strength. Such a current is called an *alternating current*. If there is an alternating voltage in a circuit, the variations in both strength and direction of the electric current correspond to the variations of the voltage. The flow of an alternating current is like the flow of water which would be produced in the pipe line in Fig. 19 when the water is agitated by a paddle moving back and forth rapidly over a short distance. In that case, the water simply surges, first in one direction, then in the other direction. It no sooner attains speed in one direction than it is compelled to slow up and then accelerate in speed in the opposite direction, and so on, over and over again. An object placed in the water will not travel around the pipe circuit, but will simply oscillate back and forth.

The alternating current which is used for most electric light circuits changes its direction, or alternates, one hundred and twenty times per second. That is, it is said to have a *frequency* of 60 cycles per second. The radio currents most used, however, may have frequencies ranging from 10,000 to 30,000,000

corresponding to wave lengths of 30,000 to 10 meters, respectively.

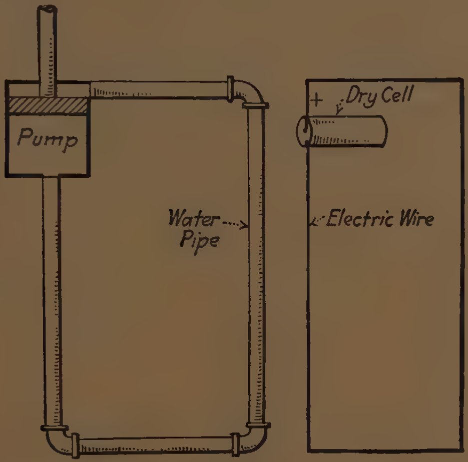


FIG. 19.—Pipe and pump line to illustrate analogy to electric circuit.

In order to distinguish the directions of flow, we call one direction the positive (+) and the other the negative (−) direction. During the flow in one direction, the strength of

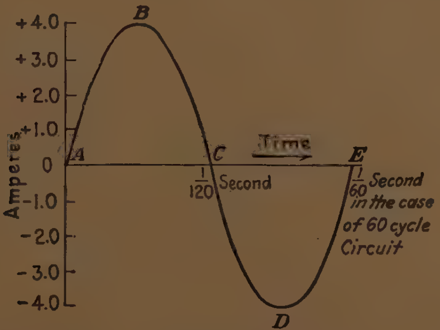


FIG. 20.—Diagram showing variations of alternating current with time (one cycle).

the current varies from zero to a maximum and back to zero again. Figure 20 shows a simple way of indicating the variations in strength, direction, and time when an alternating cur-

rent is considered. The positive direction of flow is from A to C, the negative from C to E. During the flow from A to C, the strength of the current varies from zero to a maximum, and again to zero, as shown by the curve ABC.

It is important to remember that the resistance offered by a circuit to the flow of an alternating current, that is, one which reverses periodically in direction and varies in strength, is not the same as the resistance to the flow of a direct current, that is, one which is steady in value and flows in one direction.

Capacity.—A device which is so arranged that it has a large electrostatic capacity within a small space is called a *condenser.* Essentially, it consists of two groups of plates which are insulated from each other.

A condenser used with inductance (see page 39) can be made to tune the circuit to a definite wave length. A condenser may be inserted into a circuit to by-pass an alternating current around some other part of the circuit. It may be used also to prevent the flow of direct current in a circuit.

A steady voltage is not able to pass a steady current through a condenser. When the circuit is first closed, a charging current flows until the voltage between the plates of the condenser has risen to the same value as the applied voltage. If this applied voltage is then removed and the circuit completed by a wire, a discharge current flows out of the condenser in the opposite direction to the charging current.

For a given condenser, the charge Q is proportional to the applied voltage E. This relation may be written $Q = CE$ where C is a constant called the "capacity" of the condenser. The unit of capacity is the *farad.* A farad is the capacity of a condenser in which a voltage difference of 1 volt gives the condenser a charge of 1 *coulomb*[1] of electricity. The farad is a unit which is too large for practical purposes and it is usual to use the microfarad (one millionth of a farad) and the micro-microfarad (one millionth of a microfarad).

During the time the charge is accumulating in a condenser the voltage Q/C due to this charge is increasing. This voltage

[1] A coulomb is the quantity of electricity furnished by a current of 1 ampere in 1 second.

tends to oppose the charging voltage and when Q/C becomes equal to E the charging process comes to an end. It will be noticed that the equation $Q = CE$ does not contain a time factor; therefore, the same amount of charge is stored in a condenser whether it is built up slowly or quickly. However, the rate of building up the charge depends upon the value of the capacity and resistance of the circuit. The larger the product of the factors C and R the greater is the time required to arrive at any given fraction of the applied voltage. This product $(C \times R)$ is called the *time constant* of the circuit.

The charging current I at any time after the circuit is closed is,

$$I = \frac{E}{R}\left(K\right)^{-\frac{t}{CR}}$$

where

C = capacity in farads.
E = applied voltage in volts.
R = total resistance of circuit in ohms.
t = time in seconds.
K = 2.7128.

When $t = CR$, $I = 0.368E/R$, that is, the charge reaches 63.2 per cent of its final value and the charging current drops to 36.8 per cent of its initial value in a time CR.

Condensers in Parallel and in Series.—A group of three condensers connected in parallel is shown in Fig. 21. All of these condensers are subjected to the same impressed voltage and each accumulates a charge proportional to its capacity. Since capacity is proportional to plate area, it is obvious that the method of connecting condensers in parallel has the effect of increasing the plate area of the condensers. A *parallel connection of condensers* gives a capacity which is larger than that of any one of the group. If C is the equivalent capacity of the group and c_1, c_2, c_3 the capacities of the condensers respectively, then $C = c_1 + c_2 + c_3$.

A group of three *condensers connected in series* is shown in Fig. 22. *Each condenser accumulates the same charge Q*, and the total voltage is subdivided among the condensers in inverse

ratio to their capacities. A series connection of condensers gives a capacity which is smaller than that of any of the group. If e_1, e_2, e_3 are the voltages across the condensers c_1, c_2, c_3 respectively then

$$E = e_1 + e_2 + e_3$$

and since $E = Q/C$ then

$$\frac{Q}{C} = \frac{Q}{c_1} + \frac{Q}{c_2} + \frac{Q}{c_3}.$$

FIG. 21.—Condensers in parallel.

FIG. 22.—Condensers in series.

It follows that

$$\frac{1}{C} = \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3}$$

and

$$C = \frac{1}{\frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3}}.$$

Magnetic Field of a Wire Carrying Current.—A conductor carrying an electric current is surrounded by a magnetic field similar to that of the familiar magnet. The strength of the field is proportional to the current strength. The direction of the magnetic field is given by the direction in which the fingers point if it is imagined that the right hand is closed and the thumb points in the direction of current flow. These relations are shown in Fig. 23. The direction of the magnetic field reverses when the current reverses. An alternating

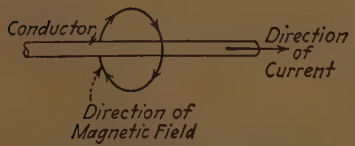


FIG. 23.—Diagram of relative directions of current and magnetic field.

current produces an alternating magnetic field which has the same frequency as the current and reverses with the current.

Induced Voltage.—The strength of the magnetic field set up in a coil of wire by a current varies with the current. When the strength of the magnetic field through a coil is varied, a voltage is induced in the coil. This induced voltage acts in a direction to oppose the change of current which is producing it; that is, when the current is decreasing, for example, the direction of the induced voltage is such as to oppose the decrease of current. The value of the induced voltage is $e = -N\frac{d\phi}{dt}$ where N is the number of turns in the coil and $d\phi/dt$ represents the rate of change of the magnetic field with time. The negative sign shows the relation between the direction of induced voltage and the change in the magnetic field.

Self-induction.—The value of voltage induced in a coil may also be expressed,

$$e = -L\frac{di}{dt}$$

in which

e = instantaneous value of induced voltage in volts.
L = coefficient of self-induction in henrys.
I = current in amperes.
t = time in seconds.
$\frac{di}{dt}$ = rate of change of current I with time.

That is, the voltage induced in a circuit equals the product of the self-inductance by the rate of change of current. The unit of self-induction is such that a coil has a self-induction of 1 *henry* if a rate of current change of 1 ampere per second gives an induced voltage of 1 volt. For practical work, smaller parts of a henry are used, such as the *millihenry* (one thousandth of a henry) and the *microhenry* (one millionth of a henry).

Mutual Induction.—A mutual voltage is induced in a coil A adjacent to another coil B carrying a changing current. The mutual voltage induced depends upon the rate of change of the

current in B and the mutual induction of the coils. This may be expressd as,

$$e_A = -M\frac{di_B}{dt}$$

in which,

e_A = voltage induced in coil A.
M = coefficient of mutual induction of the coils in henrys.
I_B = current in coil B in amperes.
$\frac{di_B}{dt}$ = rate of change of current with time.

In this equation M is measured in the same units as L and decreases as the number of turns in either coil is decreased and as the distance between the coils is increased.

Coefficient of Coupling.—Coupling determines the extent to which the field of one coil links all the turns of another coil. The coefficient of coupling k is expressed as $k = \frac{M}{\sqrt{L_1L_2}}$ in which

M = mutual induction between two circuits in henrys.
L_1 = total self-induction of one circuit in henrys.
L_2 = total self-induction of the other circuit in henrys.

Inductances in Series and in Parallel.—Inductances in series add like resistances. If the coils are so far apart that mutual inductance is negligible, inductances in parallel combine like resistances in parallel. If mutual inductance is considered the total value of inductances in series is

$$L = L_1 + L_2 + L_3 + \cdots + 2(M_{1-2} + M_{1-3} + M_{2-3} + \cdots).$$

Some or all of the mutual inductances may be negative. For two coils in parallel the total inductance is

$L = \frac{L_1L_2 - M^2}{L_1 + L_2 - 2M}$. The term $2M$ changes sign if M is negative.

Alternating Voltage.—A pure sine wave of voltage may be expressed as $e = E_0 \sin wt$

in which

e = instantaneous value of voltage at a time t in volts.
E_0 = maximum value of voltage in volts.
w = $2\pi f$ in which f is frequency in cycles per second.
t = time in seconds.
π = 3.1416.

If this equation is plotted it gives the diagram of Fig. 24. The voltage alternates in direction. That is, beginning at *a*, it goes through a set of positive changes, then a set of negative changes, and begins to repeat the cycle at *b*.

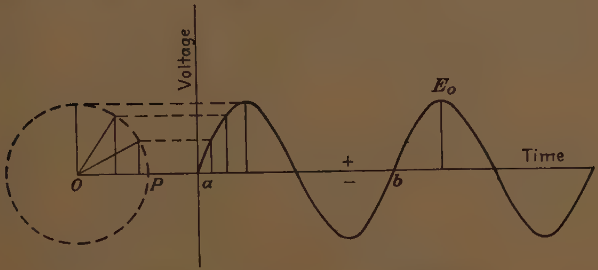


Fig. 24.—Pure sine wave of voltage.

Effective Values of Alternating Quantities.—The instruments used to indicate the strength of alternating currents and voltages show effective values which are equal to 0.707 of the maximum values. That is, the effective value E of an alternating voltage having a maximum value of E_0 is $E = 0.707E_0$. Similarly $I = 0.707I_0$.

Resistance and Inductance in Series.—When an alternating voltage with a sine wave is applied to a circuit containing resistance R in ohms and inductance L in henrys, the current which flows also is a sine wave. The current[1] is given by $I = \frac{E}{\sqrt{R^2 + w^2L^2}}$ where I and E are the effective values in amperes and volts. The quantity $\sqrt{R^2 + w^2L^2}$, called the "impedance," depends upon frequency as well as on resistance and inductance. The current lags behind the voltage by the phase angle of which the tangent is wL/R.

If the above equation is written as $E = \sqrt{R^2I^2 + w^2L^2I^2}$ it is seen that E has a value equal to the diagonal of a rectangle having sides of RI and wLI as in Fig. 25. Therefore E may be determined from a so-called "vector" diagram shown in Fig. 26 in which wLI is represented as a vector perpendicular to

[1] Cohen, L., "Calculation of Alternating Current Problems," McGraw-Hill Book Company, Inc.

RI. The current is used as the reference line. The vector RI, being a voltage in phase with the current, is drawn in the same direction as I. The voltage vector wLI across the inductance leads the current by 90 degrees. The current and voltage differ in phase by the angle θ whose tan is wL/R.

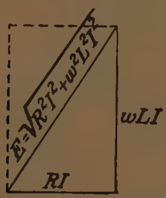


FIG. 25.—Vector diagram of alternating current and voltage.

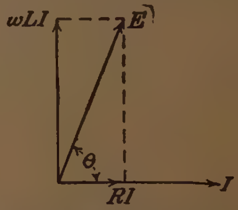


FIG. 26.—Vector diagram for determining resultant value of alternating voltage.

Resistance and Capacity in Series.—When a resistance and a capacity are in series in a circuit the relation between effective current and voltage is

$$I = \frac{E}{\sqrt{R^2 + \frac{1}{w^2C^2}}}, \text{ and } \tan\theta = -\frac{1}{wRC}.$$

Resistance, Inductance, and Capacity in Series.—When resistance, inductance, and capacity are in series in a circuit, the relation between effective current and voltage is

$$I = \frac{E}{\sqrt{R^2 + \left(wL - \frac{1}{wC}\right)^2}}$$

in which C is the capacity in farads. The terms containing L and C have opposite signs and thus one tends to neutralize the other. When capacity of a suitable value, therefore, is put into an inductive circuit, the impedance is reduced and the current increased. The phase angle θ is given by $\tan\theta = \frac{wL}{R} - \frac{1}{wRC}$.

If the above equation is written as

$$E = \sqrt{(RI)^2 + \left(wLI - \frac{I}{wC}\right)^2}$$

it is seen that E is the resultant of the three vectors RI, wLI and I/wC as drawn in Fig. 27. These quantities are the voltages across the resistance, inductance, and capacity, respectively. The vector I/wC is drawn opposite in direction to wLI because it lags behind the current by 90 degrees. The phase angle between E and I is θ and $\tan\theta = \frac{wL}{R} - \frac{1}{RwC}$, as above.

If wL is greater than $1/wC$, E is above the horizontal, θ is positive, and I lags behind E. If wL is less than $1/wC$, E is below the horizontal, θ is negative and I leads E.

If the voltage vectors in Fig. 27 are divided by I there remain the resistance R, the term wL which is called the inductive reactance X_L, and the capacity reactance $1/wC$ or X_C, all of which are expressed in ohms. These combine to give the impedance Z in ohms. Thus, $\tan\theta = \frac{X_L - X_C}{R}$.

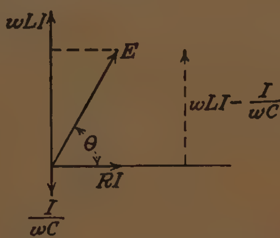


FIG. 27.—Vector diagram showing voltages across resistance, inductance and capacity.

Resistance and Capacity in Parallel.—When an alternating voltage E is applied to a parallel combination of R and C the relation between current and voltage is

$$I = E\sqrt{\frac{1}{R^2} + w^2C^2}$$

and I leads E by the angle θ where $\tan\theta = RwC$. Here the *admittance*[1] (ratio of I to E) is $\sqrt{\frac{1}{R^2} + w^2C^2}$.

In series circuits the voltages and impedances combine vectorially. In parallel circuits the currents and admittances combine vectorially.

The vector diagram for the circuit above is given in Fig. 28. The voltage E is taken as the reference line. The current vector E/R is in phase with E and the current wCE leads E

[1] Admittance is the reciprocal of impedance.

by 90 degrees. The resultant current I leads E by the angle θ where $\tan\theta = RwC$.

Resonance.—In a circuit containing resistance, inductance, and capacity in series, the current is a maximum and the impedance a minimum at the condition of resonance or when $wL = 1/wC$. The equation for current then becomes $I = E/R$ so that the impressed voltage is equal to IR. The voltage drops across the inductance and capacity may be much greater than E but, being equal and opposite, they neutralize each other. This may be shown vectorially by assuming a decreasing frequency for the circuit of Fig. 27. Then wL

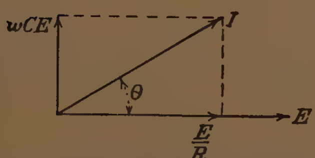


FIG. 28.—Vector diagram showing alternating voltages across resistance and capacity in parallel.

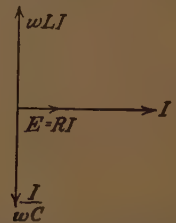


FIG. 29.—Vector diagram showing current and voltage relations when total reactance is zero.

decreases while $1/wC$ increases and when they are equal, the total reactance is zero, angle θ is zero and $E = RI$ as in Fig. 29. At a given frequency resonance may be obtained by changing L or C. Or, for given values of L and C it may be obtained by changing the frequency. Since at resonance $wL - \frac{1}{wC} = 0$ the resonant frequency is $w = 1/\sqrt{LC}$ or $f = 1/2\pi\sqrt{LC}$ where L is in henrys and C in farads, or $f = 159{,}200/\sqrt{LC}$ where L is in microhenrys and C in microfarads. The resonant wave length $= 1884\sqrt{LC}$ where L is in microhenrys and C in microfarads.

Resonance Curve. Tuning.—At frequencies other than the resonant frequency f_r, X_L and X_C are unequal and their difference enters the expression for impedance. At frequencies less than f_r, X_C is larger than X_L so that at low frequencies the current is reduced by the capacity while at high frequencies it is reduced by the inductance. At any condition other than

resonance, whether due to changes in f, L, or C, the current is reduced. The process of changing L or C to put a circuit in resonance with the frequency of an impressed voltage is called *tuning*.

The reduction of the current on both sides of the point of resonance may be shown by a resonance curve in which the square of the current is drawn against capacity when E is constant. The curve in Fig. 30 is drawn for a circuit in

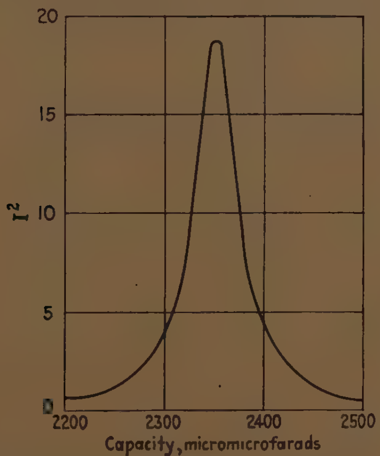


FIG. 30.—Resonance curve (variations of the square of the current with capacity).

which $R = 4.4$ ohms, $L = 377$ microhenrys, $f = 169{,}100$ cycles per second, and the applied voltage $E = 19.2$ volts. The values for I^2 are obtained from the expression $I^2 = \dfrac{E^2}{R^2 + \left(wL - \dfrac{1}{wC}\right)^2}$ as C is varied from 2,200 to 2,500 micro-microfarads.

The value of impressed voltage E must equal RI_r where I_r is the current at resonance. I_r is seen to be $\sqrt{19}$ so that $E = 4.4\sqrt{19} = 19.2$ volts. The voltage across the inductance at resonance $= wLI_r = 2\pi \times 169{,}100 \times 377 \times 10^{-6} \times \sqrt{19} =$

1,750 volts. The voltage across the condenser at resonance = I_r/wC_r, which is also 1,750 volts.

These voltages are much greater than the applied voltage of 19.2 volts. If the resistance of the circuit is increased, the current at resonance is decreased in a somewhat greater proportion.

The "sharpness" of resonance, or *selectivity*, is a quantity which indicates the fractional change in current for a given fractional change in either C or L at resonance. It may be shown that the sharpness of resonance thus defined is equal to the ratio of X to R which is equal to X_L/R and also to X_C/R.

Parallel Resonance.—In a circuit which consists of a condenser in parallel with a coil and its resistance, as shown in

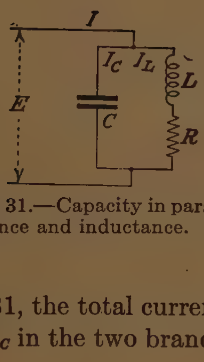


FIG. 31.—Capacity in parallel with resistance and inductance.

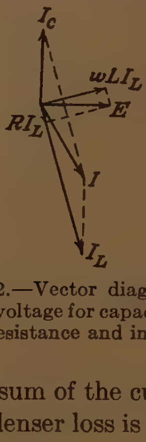


FIG. 32.—Vector diagram of current and voltage for capacity in parallel with resistance and inductance.

Fig. 31, the total current I is the vector sum of the currents I_L and I_C in the two branches. If the condenser loss is neglected

$$I_C = -wCE \text{ and } I_L = \frac{E}{\sqrt{R^2 + w^2L^2}}.$$

The sum of the two currents with consideration for their phase relation is

$$I = E\sqrt{\left(wC - \frac{wL}{R^2 + w^2L^2}\right)^2 + \left(\frac{R}{R^2 + w^2L^2}\right)^2}.$$

The vector diagram is shown in Fig. 32. At the condition of parallel resonance when $wC = \dfrac{wL}{R^2 + w^2L^2}$ the total current is

in phase with E and is equal to $I_r = \dfrac{ER}{R^2 + w^2L^2}$. The total current in the external circuit is then less than the current in the coil.

When the coil resistance is small compared with the coil reactance (as at radio frequencies) parallel resonance occurs when $w_rC = 1/w_rL$ where w_r is the value of w at resonance. The total current is then $I_r = ER/w_r^2L^2$. As shown in the vector diagram of Fig. 33, I_C is very nearly equal to I_L. The total current, being the vector sum of I_C and I_L, may be very small. The equivalent effect of the coil and condenser together upon the total current is that of a large impedance having a value of $w_r^2L^2/R$. The value of total current increases, on both sides of the point of resonance, if the inductance, or capacity, or frequency is changed, as shown in the resonance curve of Fig. 34 which is drawn for a circuit

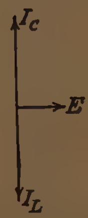


FIG. 33.—Vector diagram of current and voltage for condition of parallel resonance.

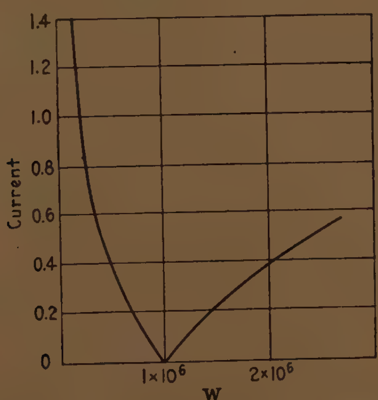


FIG. 34.—Resonance curve (parallel circuits).

having L = 377 microhenrys, C = 0.00235 microfarad, as w is varied. At low frequencies the current is increased by the effect of the capacity, and at high frequencies by that of the inductance.

Thus, in parallel resonance the coil and condenser currents are greater than the total current and the equivalent impedance is very large. In series resonance the coil and condenser voltages are greater than the resultant voltage and the equivalent impedance is very small. The current in series resonance is increased in the same proportion that it is decreased in parallel resonance.

Reactance Curves for Series Circuit.—The properties of a radio circuit may be brought out conveniently by a graphical

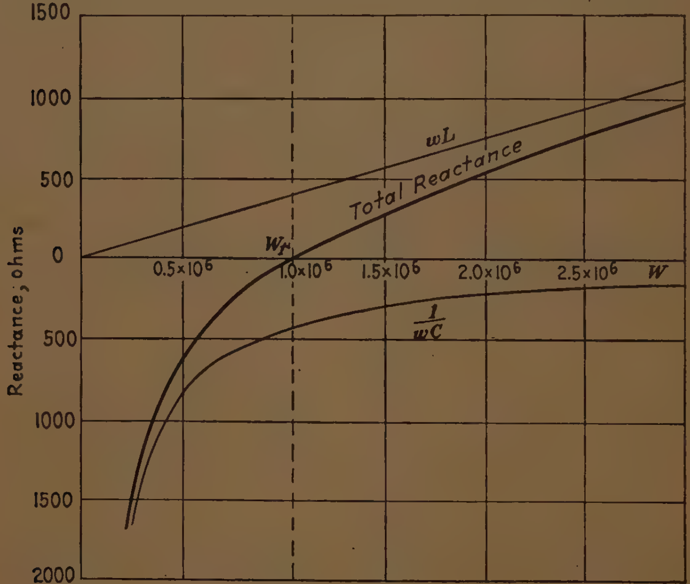


FIG. 35.—Curves showing variation of reactance with frequency for series circuits.

study of reactance curves which show how the circuit reactance varies with frequency. It is assumed that resistance is a negligible part of impedance except at resonance.

Thus, in the case of a circuit consisting of a coil of 377 microhenrys in series with a condenser of 0.00235 microfarad, the reactance of the circuit is $wL - \frac{1}{wC}$. The variation in the inductive reactance wL with frequency is shown in Fig. 35.

It is seen that wL is the greater at high frequencies. At low frequencies the capacity reactance $1/wC$ predominates. The $1/wC$ line is drawn below the horizontal to show that it is negative. The sum of wL and $1/wC$ is given by the curve marked "total reactance." The total reactance curve crosses the axis at the point w_r where $wL = 1/wC$. At that point the current is a maximum, limited by the resistance of the circuit, and the resonance curve shows a peak.

Reactance Curves for Parallel Circuit.—In a circuit consisting of the coil and condenser mentioned above in parallel,

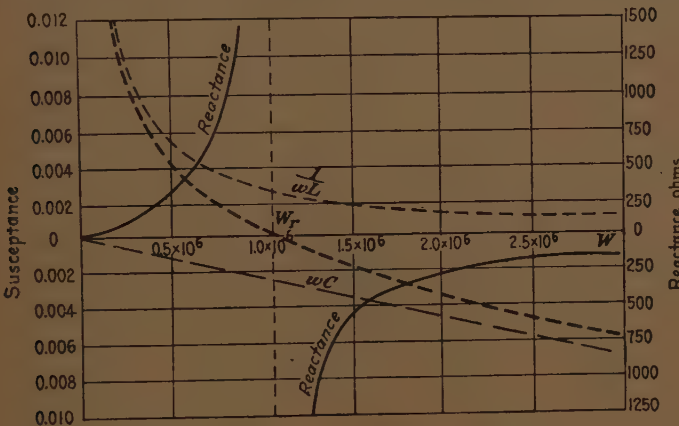


Fig. 36.—Inductive susceptance and capacity susceptance as they affect reactance curves for parallel circuits.

the reactance relations are very different. The voltage impressed across the condenser, and across the coil, is the applied voltage E. The total current is the sum of the currents I_L and I_C; that is,

$$I = \frac{E}{wL} - wCE.$$

The ratio I/E is the reciprocal of impedance. When the resistance may be neglected, this quantity is called the *susceptance*. Similarly, when resistance may be neglected, the reciprocal of the inductive reactance is the inductive susceptance $1/wL$, and the reciprocal of the capacity reactance is

the capacity susceptance wC. In this circuit the total susceptance is made up of two parts, the inductive susceptance $1/wL$ which predominates at low frequencies, and the capacity susceptance wC which predominates at high frequencies. The reactance curves for these conditions are shown in Fig. 36. The dotted curve of "total susceptance" is the sum of curves $1/wL$ and wC. The curve marked "reactance" is obtained by taking the reciprocals of points on the total susceptance curve. At the low and also at the high frequencies the circuit reactance is small, but at w_r, which is the point of parallel resonance, the value of the reactance increases to infinity. At w_r the current is a minimum and would be zero if there were no resistance in the circuit.

These two cases show that in a series circuit of L and C the reactance is zero when $wL = 1/wC$, and in a parallel circuit the reactance is infinite. When a current of a given frequency, therefore, is to be a maximum the series circuit is used, and when the current is to be a minimum the parallel circuit is used.

Reactance Curves for Coupled Circuits.—The more complicated circuits may be considered as combinations of the simple circuits which have already been described. Usually a certain portion of the complex circuit may be associated with each of the component simple circuits. This common portion is called the coupling between the circuits. Thus the circuit of Fig. 37 may be said to consist of a simple series circuit and a simple parallel circuit. The circuit C_1L is coupled to the circuit C_2L by means of the coil L.

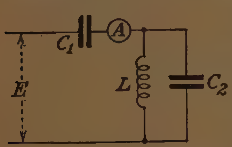


FIG. 37.—Diagram of coupled circuit.

The inductance of L is 377 microhenrys. The capacity of C_2 is 0.00235 microfarad and of C_1 is 0.00300 microfarad. The reactance curve of L and C_2 in parallel is marked X_2 in Fig. 38. Since this circuit is in series with C_1 the reactance curve X is obtained by adding the reactance curve $1/wC_1$ to curve X_2. X is the reactance to the current indicated on ammeter A. The reactance is zero at a frequency corresponding to w^1, and the current is a maximum. The reactance is infinite at w_0 and the current is a minimum. A circuit of this kind may be used

when it is necessary to pass a current of one frequency but to bar a current of another frequency. The circuit C_2L is first tuned to resonance with the frequency which is to be barred. Then condenser C_1 is adjusted until the main circuit is in

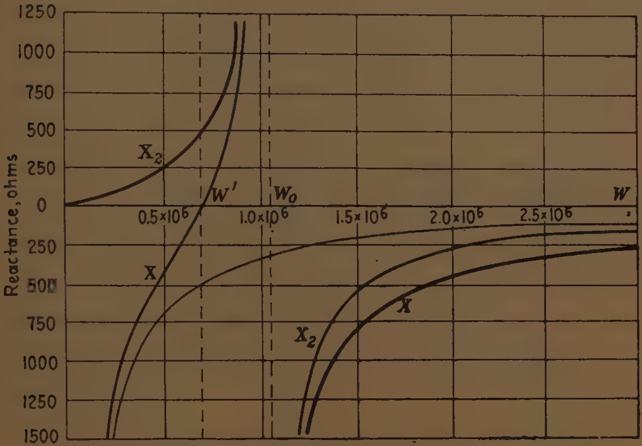


FIG. 38.—Reactance curves for simple coupled circuit.

resonance with the desired frequency. Interference is easily eliminated in this way if the circuit resistances are low.

Several modifications of this circuit arrangement are possible. For instance, instead of a condenser only, a condenser and coil in series may be connected around the inductance as shown in Fig. 39. The circuit L_1C_2 is tuned to the undesired frequency. The main circuit is then tuned to the desired frequency. The reactance to the first is thus made large, and small to the second. The reactance of the parallel combination of L with L_1 and C_2 is shown in Fig. 40 as the curve X_2 having two branches. The values of this curve, added to the condenser effect $1/wC_1$, give the reactance curve X which is shown by a heavy line. This is the reactance to the current flowing in the circuit as indicated by an ammeter A.

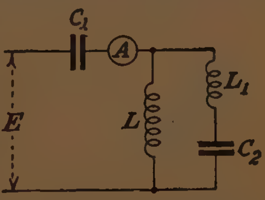


FIG. 39.—Diagram of complex coupled circuit including capacity and inductance in series.

The characteristic of coupled circuits shown in Fig. 40 is the occurrence of zero reactance at two frequencies w' and w'' at each of which the current is a maximum. At the intermediate frequency w^0 the reactance is infinite and the current a minimum (if the circuit resistances are small). With a circuit of this kind it is possible to exclude one frequency and tune to another frequency either greater or less than the one excluded.

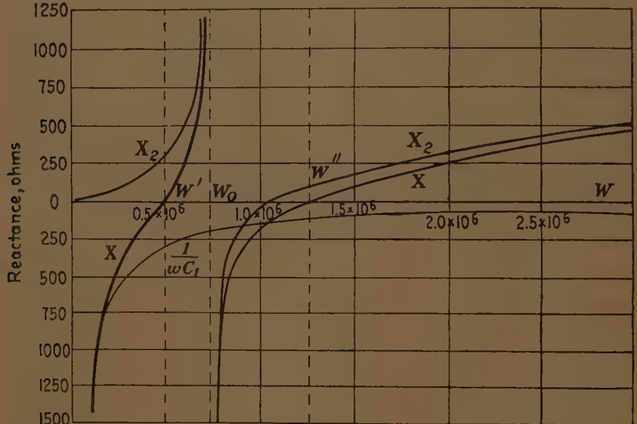


FIG. 40.—Reactance curves for complex coupled circuit.

Coupling.—When two circuits are *coupled* or connected together, the one to which power is applied is the primary and the other the secondary. Two circuits may be coupled together as shown in Fig. 41; (a) by a direct connection across a common inductance, (b) by induction through mutual inductance, (c) by direct connection across a common capacity. The coupling is *tight*, or *loose*, depending on whether the resulting mutual inductance is a large or a small part of the possible maximum. When the coupling is very loose, however, the back action of the secondary on the primary may be neglected and the two act as independent circuits.

The degree or *coefficient of coupling* k for type (a) is given by $k = M/\sqrt{L_1L_2}$ where M is the mutual inductance, L_1 the *total* inductance of the primary, and L_2 that of the secondary. For type (b), $k = M/\sqrt{L_1L_2}$ where L_1 and L_2 are the *total*

inductances of the primary and secondary, respectively, each measured with the other circuit removed. For type (c), $k = \sqrt{C_1C_2}/C_m$ where C_1 is the *total* capacity of the primary, C_2 that of the secondary, and C_m the mutual capacity.

Any of these types of coupled circuits may be used to exclude an objectionable frequency and to respond to another frequency either lower or higher than the one excluded, if the circuit resistances are small.

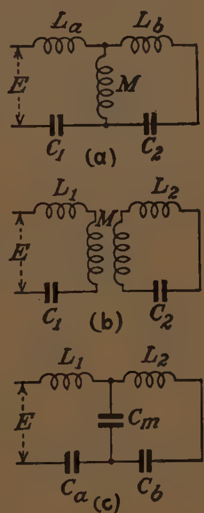


FIG. 41.—Diagram of various types of coupled circuits.

Direct Coupling.—The reactance curves for a combination like that of type (a) (Fig. 41) are similar to those of Fig. 40. In considering the action, it is convenient to use the terms w_1 and w_2 for the respective values of the frequency w at resonance in the primary circuit L_aMC_1 alone and in the secondary circuit L_bMC_2 alone.

When

$$w_1 = w_2$$

then

$$w' = \frac{w_1}{\sqrt{1+k}}$$

and

$$w'' = \frac{w_1}{\sqrt{1-k}}.$$

When the value of k is small (when M is small compared with L_a or L_b) then $w' = w'' = w_1$. In this case, with loose coupling, the whole circuit instead of being resonant to two frequencies is resonant to but one, that of either circuit alone. If, however, the coupling is close, k approaches unity, and the two frequencies become separated with the limiting values $w' = w_1/\sqrt{2}$ and $w'' =$ infinity. Practically there is only the frequence $w' = 1/\sqrt{2MC_1}$ and the reactance curve becomes that of Fig. 37.

Inductive Coupling.—The action of an inductively coupled circuit (Fig. 41b) is the same as that of the direct-coupled system. The reactance curves are the same and the fre-

quencies w' and w'' at which the current is maximum are the same. The expressions for w_1, w_2, and k are $w_1 = 1/\sqrt{L_1C_1}$, $w_2 = 1/\sqrt{L_2C_2}$, $k = M/\sqrt{L_1L_2}$.

The variation of current with the coupling[1] depends, also, upon the resistance R_1 of the primary and R_2 of the secondary. When both the primary and secondary are tuned $w =$

$$\frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}, \; I_1 = \frac{ER_2}{R_1R_2 + w^2M^2},$$

and

$$I_2 = \frac{EwM}{R_1R_2 + w^2M^2}.$$

The current I_2 is a maximum, if M is varied, when $w^2M = R_1R_2$.

Capacity Coupling.—The action of a system having capacity coupling is similar to that of the direct-coupled circuit. When $w_1 = w_2$ then $w' = w_1\sqrt{1 + k}$ and $w'' = w_1\sqrt{1 - k}$. If the coupling is loose, k approaches zero and $w' = w'' = w_1$ in which case the system is resonant to the resonant frequency of either circuit alone. If the coupling is close (C_m is small as compared with C_a and C_b) $w' = \sqrt{2}w_1$ and $w'' = 0$. That is, the system is resonant to practically but one frequency, $w' = \sqrt{2/L_1C_m}$.

Resonance in Coils.—The effect of the distributed capacity of a coil, that is, the capacity between the turns, usually may be neglected at low frequencies, but has considerable importance at high frequencies. For most purposes a coil may be regarded as an inductance in parallel with a small capacity. In such a coil the reactance increases with frequency to infinity at the point of parallel resonance. Beyond this value of frequency the coil no longer acts as an inductance.

[1] Stone, J. S., "Maximum Current in the Secondary of a Transformer," *Physical Review*, Vol. 32.

CHAPTER IV

VACUUM TUBE ACTION

Electron Emission.—The tendency of a metal to evaporate, just as water evaporates at ordinary temperatures, is due to the tendency of the atoms of the metal to separate from each other at temperatures that are high enough to give them the necessary velocity.

The electrons associated with an atom are in motion at a rate which increases with increasing temperature. When a metallic filament is heated to incandescence, the atomic agitation of the substance is increased and the motion of its electrons becomes so rapid that some of them break away. The escape of electrons in this way occurs at a temperature which is lower than that necessary to produce *atomic* evaporation, for the reason that the velocity of the electrons is greater than that of the atoms. At the surface of a metal, according to the theory of Richardson,[1] the electrons are restrained from leaving the metal by electric forces entirely similar to the molecular forces which cause the surface tension of a liquid.

In the absence of any external electrical attraction most of the electrons return to their former position when cooled because the filament is left positively charged and exerts an attractive force on them. At the same time the electrons already present in the space exert a repelling force on those leaving the filament. This setting free of electrons by a body when it is heated is called *electron emission.* The presence of such free electrons in the space surrounding a heated body makes this space a good conductor of electricity.

Emission Current.—When a suitable bulb, from which the air has been removed to obtain a vacuum, contains a filament

[1] Richardson, A. W., "Theory of Thermionic Emission," *Philosophic Trans.*, Vol. 202, p. 516.

near the middle and a metallic plate close to it, and the filament is heated, a few electrons will leave the filament with sufficient velocity to reach the plate. If this plate in the bulb is *entirely* insulated, the electrons which accumulate on it will soon build up a charge sufficient to prevent a further flow of electrons from the filament. If, however, instead of being insulated, the plate is connected by a conductor to the filament, large numbers of electrons will flow across the space to the plate and back to the filament through the connecting conductor. This current, due to electron emission, is called the *plate current.*

The plate current is greatly increased if a battery is connected into the circuit between the plate and the filament so as to create a positive potential or voltage on the plate.

Characteristic Curves.—The performance of vacuum bulbs or tubes in radio communication is studied by the use of curves which show their characteristic properties. The performance of a simple electrical device incorporating an ordinary ohmic resistance can be determined from a knowledge of only one property of the device—its *ohmic resistance.* On the other hand, the performance of vacuum tubes is shown by diagrams from which a determination can be made of all the possible combinations of voltages and currents that may occur in practice. These diagrams, known as *characteristic curves*, are easily obtained by keeping the filament voltage constant, and varying the applied voltages, and reading the resulting currents that flow.

Two-element Vacuum Tubes.—A two-element tube consists of a metallic filament and a metallic plate sealed in a glass bulb in which there is a vacuum. The filament may be heated by a current from a battery. The plate is made positive with respect to the filament by connecting a battery in the plate-to-filament circuit. Under these conditions, as explained before, a flow of electrons takes place from the filament to the plate. As the *plate voltage* is increased a point is reached at which all the electrons emitted from the filament are drawn to the plate. Hence, any additional increase in plate voltage is not accompanied by any increase in plate

current by electron emission. This maximum value of emission is called the *saturation current* and, because it is an indication of the total number of electrons emitted, it is also called the *emission current* or *filament emission.* This condition is shown at point A in the curve of Fig. 42. The bend in the curve shows that when the plate voltage has been made large enough there is little further gain in the plate current. Under these conditions the *plate current can be increased,* however, by increasing the filament temperature. The explana-

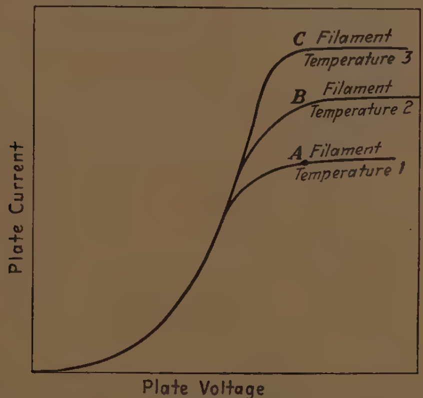


FIG. 42.—Relation of plate current to plate voltage when filament temperature is varied.

tion of this is that the number of electrons sent out by the filament increases with the temperature approximately as the square of the excess of the filament temperature above a red heat, and, thus, more electrons are available to be drawn over to the plate. For any temperature of the filament there is a corresponding maximum value of plate current. This maximum is reached when the electrons are drawn over to the plate at the same rate as they are emitted from the filament. The effect of varying the temperature of the filament is shown by the curves A, B, and C in Fig. 42.

On the other hand, if the plate voltage is kept constant, and the filament temperature is raised by increasing the filament current, the emission current or filament emission is increased.

The plate current will increase up to a certain temperature, but beyond this temperature it will remain practically constant even though more electrons are being given off. This means that for every value of plate voltage there is a corresponding value of filament temperature beyond which no increase in plate current is obtained. This effect is shown by the curves of Fig. 43.

The explanation[1] of this behavior is that the stream of negative electrons flowing through the vacuum tube acts as a

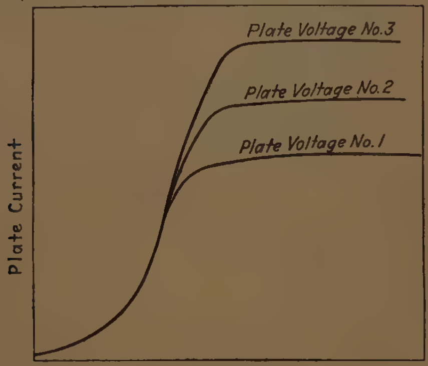


Fig. 43.—Relation of plate current to filament temperature when plate voltage is varied.

space charge of negative electricity which neutralizes the electrostatic field due to the positive plate; that is, the effect of the negative "space" charge upon the electrons leaving the filament is opposite to that of the positive charge on the plate. In consequence, only a limited number of electrons can flow to the plate per second with a given plate voltage, and the remainder are compelled to return to the filament. It is obvious, therefore, that the condition of either voltage or current under which the filament is to be operated must be specified.

For a given plate voltage the maximum possible value of plate current depends upon the spacing, size, and shape of the elements of the tube.

[1] Langmuir, I., "Theory of Electron Tubes," *Physical Review*, Vol. 2, p. 450, 1913 and *Proc. I. R. E.*, Vol. 3, p. 261, 1915.

Commercial Uses of Two-element Vacuum Tubes.—The ordinary commercial applications of two-element vacuum tubes are for the rectification of alternating current and for the production of X-rays. Vacuum tube rectifiers of alternating current are divided into two classes: (1) the tube with a hot filament and a cold plate and (2) the tube with a cold filament and a cold plate (two cold elements). The tubes with a hot filament and a cold plate may again be divided into the type which depends for its action upon the ionization of a gas, and the type which does not. The various classes of two-element tubes are summarized thus:

- Vacuum tube rectifiers....
  - Hot filament and cold-plate type.
    - Action by ionized gas
      - Tungar
      - Rectigon
    - True thermionic action
      - UX-280
      - UX-281
      - UX-213
      - UX-216B
      - Rectron
  - Two cold-elements type, Raytheon "S" tube

The *Tungar rectifier* functions because of the uni-lateral (single-direction) conductivity between a hot filament and a cold plate of the tube. The tungsten filament is the source of electrons and is maintained at the necessary temperature by a current from some external source. The tube is filled with *argon* which is an inert gas capable of being ionized by the electrons. In this type of tube the plate current is carried mostly by the ionized gas. The Tungar and *Rectigon* are examples of low-voltage rectifier tubes in which the flow of plate current depends on gaseous conduction. The filament is necessary to give stable operation at the low voltages at which the tubes are operated. Such tubes can be used under certain conditions for charging batteries with a cold, unlighted filament.

Rectifier tubes such as the UX-280 and UX-281 are of the filament type and depend on true *thermionic action* for their operation; meaning that the electrons can move from the filament to the plate, but, since the plate is not a source of

free electrons, when these electrons are once on the plate they are not released and cannot flow back to the filament. Thus, a current flows from the filament to the plate only when the plate is positive and the current stops flowing when the plate is negative. By use of this device an alternating current may be changed into a *pulsating direct current.* The maximum ratings of the UX-280 and UX-281 tubes are higher than those of UX-213 and UX-216B tubes, although their outputs at the normal operating voltages of the latter are approximately the same. Thus the UX-280 and UX-281 tubes can be used in place of the UX-213 and UX-216B, respectively.

The rectifier tubes with two cold elements or the gaseous-conductor vacuum tubes are represented by the *Raytheon rectifier* tube and by gas-filled rectifier tubes which do not have filaments. This type depends for its action entirely upon the effects of ionization by collision. The tube consists of two elements inside a glass bulb under a reduced pressure of certain gases. The elements of the tube are arranged in such a way that the electrons from one element move a relatively short distance and are absorbed before any ionization by collision with the gas particles can take place. The electrons from the other electrode must move a greater distance, and have a path which is long enough so that ionization by collision can take place and new electrons and positive *ions* can be produced. Consequently when a voltage is applied in one direction there will be a very small current due to the flow of free electrons. When the voltage is reversed there is a much larger flow of current due to the effect of ionization by collision. The rectification is not perfect because some current flows in either direction although the reversed current is nearly negligible in value. This type of tube passes current freely in one direction at about 150 volts, but requires about 700 volts to cause a flow of current in the opposite direction.

Three-element Vacuum Tubes.—It has been shown that the plate current may be influenced by changes in either filament temperature or plate voltage or both. Another factor which will influence the flow of plate current is the effect of an electrostatic charge on a third element in the tube.

The third element, which is placed between the filament and plate, is usually a set of parallel wires or a perforated plate called the *grid*. The spacing between the wires of this third element depends upon the service for which the tube is designed. The conventional representation of a three-element tube is shown in Fig. 44. The third element or the grid *G* obtains its electrostatic charge from its connection to the battery "*C*".

The filament is nearer to the grid than it is to the plate so that a voltage applied to the grid exerts a greater attractive or repulsive force than the plate upon the filament electrons. Usually, the grid is charged negatively with respect to the filament. A negative potential may be applied to the grid by connecting the positive terminal of the battery "C" to the filament and its negative terminal to the grid as shown in Fig. 44.

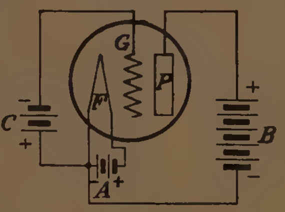


FIG. 44.—Conventional representation of three-element vacuum tubes.

The negative charge of the grid tends to force the filament electrons back to the filament. This effect, together with that of the "space" charge, repels the electrons and, consequently, reduces the value of the plate current, because no appreciable number of electrons can reach the plate. If the negative voltage of the grid is reduced, the flow of electrons to the plate is increased. If, on the other hand, the negative voltage of the grid is increased, the flow of electrons to the plate is decreased. In fact, the plate current may be reduced to zero if the negative charge on the grid is large enough.

A positive charge on the grid will neutralize the repelling effect of the "space" charge on the flow of electrons, thus causing an increase in plate current. The greater the positive charge on the grid the more the plate current will increase until it reaches as a limit the saturation current corresponding to the temperature of the filament.

When the grid is positive some of the filament electrons will be attracted to it and produce an electric current in the grid

circuit which flows from the grid to the filament, through the battery "C", and then back to the filament. This effect is shown by the curve of grid current in Fig. 44.

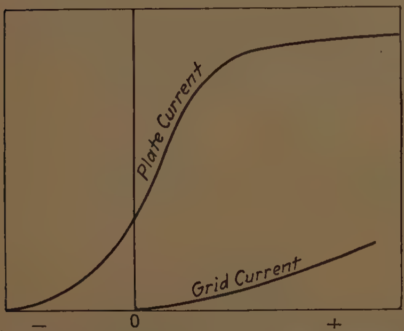


Fig. 45.—Relation between plate current and grid voltage.

The value of the grid current is relatively small so that it is usually measured in micro-amperes. The flow of current in the grid circuit may be controlled by using suitable values of the operating voltages. In the action of a vacuum tube as a detector, when a grid leak and grid condenser are used (see page 132), the grid current becomes of importance.

The relation between plate current and grid voltage is shown in Fig. 45 for a given value of plate voltage and filament temperature. If the filament temperature is kept constant

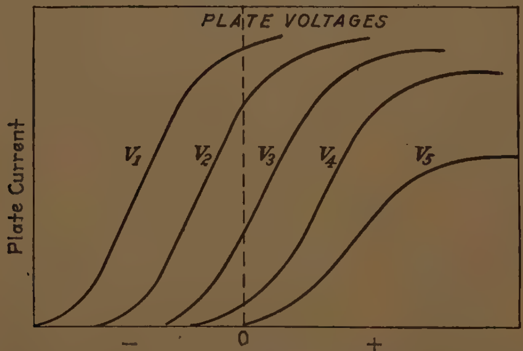


Fig. 46.—Series of curves showing relation between plate current and grid voltage for a series of values of plate voltage.

and a curve of plate current is drawn for each of a series of plate voltages a group of curves is obtained like Fig. 46. The relation between plate current and plate voltage for various grid voltages may be represented as in Fig. 47.

The electric power consumed in the input circuit of a three-element tube is very small because of the small electrostatic capacity of the grid with respect to the filament. Ordinarily, the grid circuit does not carry any current. A small change in grid voltage produces the same effect upon plate current as a much larger change in plate voltage. Thus, a small input of electric power, largely in the form of voltage on the grid, controls a much larger amount of power in the plate circuit. This characteristic permits amplification of voltage or power to be obtained by the use of a three-element vacuum tube.

The insertion of the grid element gives the three-element tube the properties of amplification and oscillation which the two-element tube does not have. These properties give this kind of vacuum tube the important place which it occupies today in radio transmission and reception.

Plate Current.—The electron current which flows from the filament to the plate of a three-element vacuum tube depends on the grid and plate voltages, the spacing and size of the grid mesh, the distance between the *elements* (filament, plate and grid), and the area of the elements supplying current.

The equation for plate current is:

$$I_p = K(E_p + uE_g)^x$$

where

I_p = plate current of the tube, amperes.
K = constant depending upon the type of tube.
E_p = plate voltage measured between the plate and the negative terminal of the filament, volts.
E_g = grid voltage measured between the grid and the negative terminal of the filament, volts.
u = amplification factor of the tube.
X = exponent, usual about 2.0.

The term E_p represents the "applied" voltage, being equal to the plate-supply voltage minus the voltage lost in the resistance of the plate circuit. In radio-frequency amplifiers, the resistance in the plate circuit may be neglected, and the applied plate voltage becomes equal to the plate-supply voltage. With resistance coupling, the voltage loss in the plate resistance is at

times large enough to consume more than one-half of the plate-supply voltage. The effect of a voltage applied to the grid is given by the term uE_g, so that the grid voltage is u times as effective in causing a plate-current change as the same plate voltage. Since the voltage which is applied to the grid is usually negative, the term uE_g lowers the "effective" plate voltage. Thus, if a UX-201A tube has 90 volts on the plate, and the grid is connected to the negative terminal of the filament, then, at zero grid voltage, the "effective" plate voltage

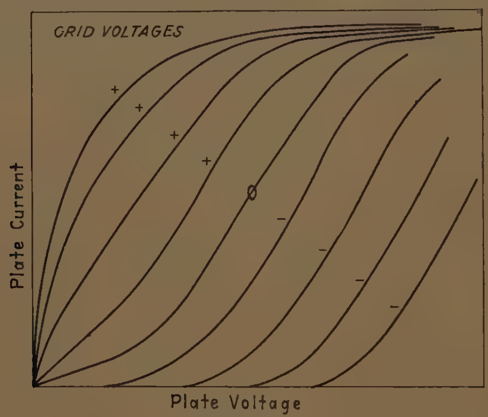


FIG. 47.—Relation of plate current to plate voltage for a series of values of grid voltage.

E is $E_p + uE_g = 90 + 8.5 \times 0 = 90$ volts, and the plate current is 6.0 milliamperes. If now the recommended value of "*C*" *battery* or *grid-bias* voltage[1] to be applied to the grid is -4.5 volts, the effective plate voltage is decreased, although the actual battery voltage remains unchanged. Then $E = E_p + uE_g = 90 + 8.5\,(-4.5) = 90 - 38.2 = 51.8$ volts, and the plate current now decreases to 2.0 milliamperes, since the effective voltage is lower.

Curves showing the variation of plate current with plate voltage are needed only to show the plate current when the grid-bias voltage is zero. The relations for other conditions can be found by determining the effective plate voltage as in

[1] See MOYER and WOSTREL, "Practical Radio," p. 79.

the example above and by applying this value to the curve to get the corresponding value of plate current.

On the other hand, if the "C" battery is connected so that the grid-bias voltage has a positive value, the effective plate voltage is higher than the applied voltage, since the term uE_g becomes positive and adds to the plate voltage E_p. Under such conditions, the grid current is large and the grid absorbs considerable power (watts), so that the efficiency of the tube as an amplifier is reduced.

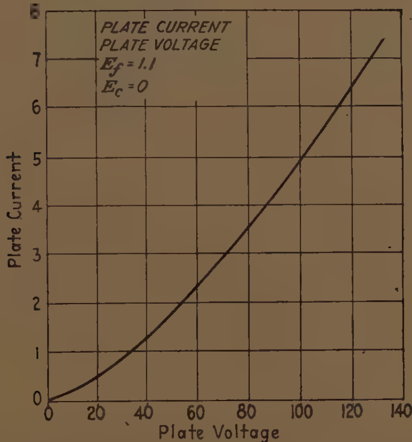


FIG. 48.—Relation of plate current to plate voltage for WX-12 vaccum tubes.

An inspection of the curves of plate current plotted against applied plate voltage as for the WX-12 tube in Fig. 48 shows that the plate current increases slowly at low plate voltages and more rapidly at higher voltages. This non-linear relation (due to the exponent X in the above equation) permits the use of the tube as a detector. This same relation makes special precautions necessary when a maximum amount of undistorted power output is required, as in power amplifiers.

The normal plate current of tubes differs widely, ranging from 20 milliamperes in the case of the UX-171A tube down to 0.2 milliamperes for the UX-240 tube. In general, a vacuum tube having a low plate resistance and low amplification factor will carry a high plate current, and vice versa.

Plate Resistance.—The internal or *direct-current* resistance R of a vacuum tube permits a current I_p to flow from the plate to the filament when the plate voltage is E_p. An estimate of this direct-current resistance of a vacuum tube may be obtained by observing the plate current corresponding to the plate voltage at which the resistance is desired. The relation between these factors may be expressed as $R = E_p/I_p$.

The vacuum tube as generally used in radio reception operates with pulsating and not constant values of grid voltage, plate voltage, and plate current. Such a pulsating current, for example, is considered to be a combination of a direct-current portion and an alternating-current portion, each of which acts independently of the other. The resistance of the tube to alternating current differs from the resistance to direct current. Unless otherwise stated, the term *plate resistance* in connection with the description of vacuum tubes is the *resistance offered to the flow of alternating current* and is designated as r_p. The *alternating-current* resistance r_p of the plate circuit may be found from the relation,

$$r_p = \frac{dE_p}{dI_p}$$

in which dE_p is a small change in plate voltage which produces a corresponding change dI_p in plate current, when the grid voltage is constant. It may be seen from this that r_p is equal to the reciprocal of the slope of the plate current-plate voltage curve at the "point of operation." This slope, and, of course, the plate resistance, is approximately constant over the straight part of the curve but shows an increase at the lower and upper bends.

The expression for the alternating-current resistance may be given also as,

$$r_p = \frac{udE_g}{dI_p},$$

in which dE_g is a small change in grid voltage which produces a corresponding change dI_p in plate current. The term udE_g is, of course, equal to the term dE_p from the preceding equation.

It is shown in Chap. 6 that the resistance of the tube to alternating current is approximately equal to half the resistance of the tube to direct current. This may be seen from the fundamental relation,

$$r_p = \frac{E_p}{2I_p} = \frac{R}{2}.$$

The plate resistance is a measure of the effect of the plate voltage alone upon the plate current. It varies because of the non-linear relationship of plate current to plate voltage shown in Fig. 48. At low values of plate voltage the plate resistance is relatively high. As the plate voltage is raised, the plate resistance decreases rapidly and then more slowly as the normal operating voltage is reached. If the applied voltage is very high, the plate resistance may again increase. This critical value indicates that the saturation point is being reached; that is, practically the full emission current is flowing. This condition is apt to occur when "dry-cell" vacuum tubes are subjected to voltages in excess of rated values, or when they are operated without a "C" battery.

If the filament emission at high plate voltages limits the plate current, the plate resistance will increase. This decreases the efficiency of a vacuum tube as an amplifier. The available emission of a UX-199 tube is approximately three times the value of the plate current (2.5 milliamperes) when the negative grid voltage is 4.5 volts and the plate voltage is 90 volts. With no grid bias the plate current becomes 5.75 milliamperes, which is close to the value of the emission current. It is obvious that a grid bias should be used with such tubes at high plate voltages.

A simple apparatus for volume control can be made to depend upon this increase in plate resistance which takes place when the emission current is near the value of the plate current. If the filament current of one or more radio-frequency amplifying tubes is decreased, the reduced emission current increases the plate resistance and thus may be used to control amplification. The distortion thus introduced by the increased slope of the curve showing the variation of plate current with plate voltage may be neglected. The life of the

tube is less, however, than if the control is accomplished by reducing the plate voltage by the method of using a series resistance in the plate circuit.

Three-element Vacuum Tube Considered as a Variable Resistance.—An interesting conception of a vacuum tube is that of a variable resistance. The curves of Fig. 47, showing the relation between plate current and plate voltage for various values of grid voltage, indicate that the three-element tube may be considered as a variable resistance, the value of which

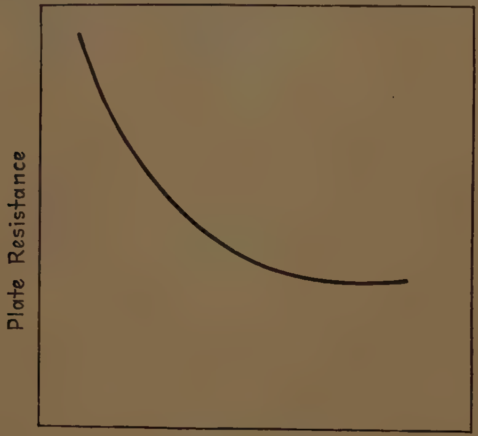


Fig. 49.—Relation of plate resistance to plate voltage at zero grid voltage.

depends upon the grid voltage; meaning that the higher the grid voltage, the less the tube resistance, and *vice versa*. As the grid voltage is varied from the negative to the positive direction, the value of plate current increases up to the saturation value. At this point, the resistance is a minimum for the given operating conditions. A curve showing the relation between the plate resistance r_p and the plate voltage E_p at zero grid voltage is given in Fig. 49. This conception of a tube is very helpful in a study of tube operation, especially for transmitting equipment.

The resistance of a vacuum tube causes a loss of power which cannot be avoided. The value of this loss of power is pro-

portional to the value of the resistance. The tube resistance depends upon certain factors of design such as the spacing between tube elements, the length and area of the filament, the temperature and condition of the filament, the efficiency of the emitting surface, the plate area, the amplification factor, and the applied voltages.

The performance of a tube may be improved if the plate resistance is reduced by changing the design factors mentioned above. The desirability of such a change, however, depends upon some other conditions. It may happen that such a change may increase power consumption to an undesirable extent. It may affect the reliability, strength, and life of the tube, or it may unbalance the circuit in which the tube is used.

Amplification Factor.—The amplification factor u is the ratio of the change in *plate voltage* dE_p to the small change in *grid voltage* dE_g which produces an equal variation in plate current; that is,

$$u = \frac{dE_p}{dE_g}.$$

The amplification factor depends upon the spacing and size of the network of wires in the grid, that is, the closer the spacing the greater the screening effect of the grid on the electrostatic field of the plate. It also varies directly as the distances between the plate and the filament, and between the grid and the filament. The nearer the grid is to the filament the smaller will be the voltage which is needed to produce a field around the filament equal to the field set up about it by the plate. Thus, a tube having a large amplification factor uses a fine grid mounted at a small distance from the filament, as compared to the distance between plate and filament.

It is evident from what precedes that the flow of electrons is influenced by an electrostatic field which is the combination of the fields due to the plate and grid charges. Therefore, the amplification factor is

$$u = \frac{C_g}{C_p}$$

where C_p is the electrostatic capacity of the condenser represented by the plate and filament and C_g is the electrostatic

capacity of the condenser represented by the grid and filament.

This relation shows that the amplification factor is a constant and depends only on the tube structure and not on the operating voltages. It explains also why the curves showing the relation of grid voltage to plate current for various constant values of plate voltage are approximately parallel to each other. The amplification factor is not affected by those factors which influence plate resistance, such as electrode area and filament condition, nor is it altered by changes in the applied voltage, except that at low plate voltages it may decrease slightly.

Actually the amplification factor u is not quite constant but varies with the grid and plate voltages. The explanation of this effect is that a change in grid and plate voltages causes a change in the shape and location of the "space" charge. This, in turn, changes the effect of the grid and plate voltages on the flow of electrons.

Furthermore, the entire filament is not at the same potential because a voltage drop exists along it. Hence the voltage difference between the grid and various parts of the filament is not constant. For example, if E is the voltage across the filament and if the grid is connected to the negative end of the filament, then the grid is at zero potential with respect to that end, but at a potential of $-E$ with respect to the positive end. Electrons can flow from the negative end of the filament without being affected by the grid because there is no voltage difference between the grid and that end of the filament. But the flow of electrons from the *positive* end of the filament may be stopped entirely by the effect of the grid which, with respect to the positive end of the filament has a negative voltage of $-E$. The influence of the grid on the flow of electrons, therefore, is not so active as when all of the filament is at the same voltage.

The amplification factor is, however, practically constant in value over the straight portion of the characteristic curve. The value of u of a vacuum tube expresses the relative effects of grid voltage and plate voltage on the plate current, and so

determines the plate resistance of the tube. An increased amplification factor corresponds to an increased plate resistance and vice versa. A change in the amplification factor also affects the *mutual conductance* (see page 72) to some extent even though the plate area, filament length, and other such factors remain constant. A tube with a high amplification factor shows a lower mutual conductance than a tube of similar construction but with a lower amplification factor. This effect is shown in Fig. 50, for a number of tubes with different amplification factors but using the filament and plate construction of a UX-120 tube. It is evident from this

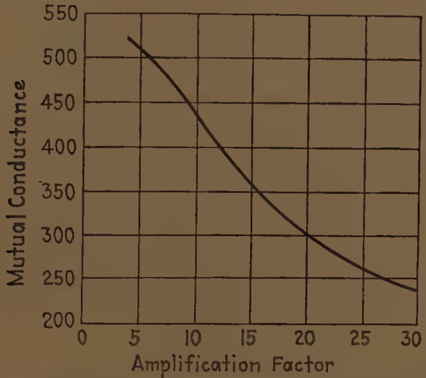


FIG. 50.—Relation of mutual conductance to amplification factor.

drawing that a low value of the amplification factor should be used in order to gain the advantage due to improved mutual conductance, provided that the *load impedance* (see page 190) can be adjusted to a suitable value. Such conditions are conducive to maximum power output. For voltage amplification in circuits in which high plate resistance is not important, as in resistance- or impedance-coupled amplification, a high value of u is desirable, because it allows an increase in voltage amplification to be obtained from each stage of the amplifier.

The amplification factor is a measure of the maximum voltage amplification obtainable from the tube alone. The grid-to-filament voltage due to the reception of a radio signal appears in the plate circuit multiplied u times. The voltage

developed across a high-impedance load placed in the plate circuit is very nearly equal to this value of uE_g.

Mutual Conductance.—Both the plate resistance and the amplification factor of a vacuum tube affect its performance as an amplifier. In comparing the merits of tubes it is convenient to use a term called "mutual conductance" which takes both of these factors into consideration. *Mutual conductance* is the ratio of the amplification factor to the plate resistance. The usual unit of mutual conductance G_m is the *micromho*. It has been shown that

$$u = \frac{dE_p}{dE_g}, \text{ and } r_p = \frac{dE_p}{dI_p},$$

hence the ratio of the first of these two equations to the second gives the mutual conductance, thus,

$$G_m = \frac{dE_p}{dE_g} \div \frac{dE_p}{dI_p} = \frac{dI_p}{dE_g} \text{ (in mhos).}$$

Or,

$$G_m = \frac{u}{r_p} \text{ (mhos)} = \frac{u}{r_p} \times 10^6 \text{ (in micromhos).}$$

That is, mutual conductance may be expressed as the ratio of a small change in plate current to the change in grid voltage required to produce the same change in plate current. This expression also represents the slope of the curve showing the variation of plate current with grid voltage at the "point of operation." The slope of the curve is greatest, of course, at the point at which the curve is steepest. In other words, at the point of largest value of the slope, a given change of grid voltage produces the maximum change in plate current.

The expressions developed for the values of amplification factor, plate resistance, and mutual conductance show that these three factors are interdependent according to the relations.

$$r_p = \frac{u}{G_m}, \; u = r_p \times G_m, \text{ and } G_m = \frac{u}{r_p}.$$

Tubes having high values of mutual conductance are more efficient amplifiers than those having lower values, but the comparison must be made between tubes *designed for the*

same service and having similar characteristics. Thus the UX-112A tube has an average mutual conductance of 1,600 micromhos with a plate voltage of 135 volts, and the UX-171A tube has an average value of 1,360 micromhos for the same plate voltage. The UX-171A tube can supply a 160 per cent greater undistorted power output than the UX-112A tube, when ample input voltage is available and the load is properly adjusted. In any case, a relatively large change in mutual conductance causes only a small change in tube performance as judged by the ear in radio reception.

Effects of Interelectrode Capacity.—The elements of a vacuum tube form an electrostatic system, each element acting as one plate of a small condenser. The capacities which exist are the grid-to-filament capacity, the grid-to-plate capacity, and the capacity of the grid-to-plate and grid-to-filament connected together. The *total* capacity of a tube is made up of the capacity of the electrodes of the tube, of the lead-in wires, and of the base. The capacity between the grid and the filament, and between the plate and the filament, is about 5 micromicrofarads. The capacity between the grid and plate is larger, being, for example, approximately 10 micromicrofarads in the UX-210A tube.

It is necessary to remember that the interelectrode capacities of a tube, as measured when the elements are *free*, are not the same as when the elements are *connected*. Thus the "direct" capacity between the grid and plate is increased by the mutual capacity from grid to filament and from filament to plate. The "direct" capacity between the grid and plate of a UX-201A tube, when the filament has been removed, averages 8 micromicrofarads, while the capacity as measured between these two elements in a complete tube is 10.1 micromicrofarads. The effective value of this capacity is further increased by the capacity of the wiring of the tube socket, the tube base, and also by the amplification action of the tube.

When a tube is in use its *input circuit* is considered to be from grid to filament, and its *output circuit* from plate to filament through a battery and some external load. Thus the

capacity of the input circuit may be considered as that of a condenser which has the grid for one plate and the plate and filament connected together for the other. If an alternating voltage is applied to the grid-to-filament circuit of a tube, an alternating current will flow in the grid circuit because of the grid-to-filament capacity. Whether the filament is lighted or not this grid voltage will set up a current in the plate circuit due to electrostatic induction through the capacity from the grid to the plate.

While the grid-to-filament capacity and the plate-to-filament capacity do not affect the performance of a tube at audio frequencies and have only a small effect at *radio* frequencies, the grid-to-plate capacity has a very marked effect in a radio-frequency amplifier. As far as the tube itself is concerned, the capacities between the elements of a tube introduce a reactance effect.

When amplification is given in terms of the applied grid voltage, the filament-to-plate capacity has only a small effect, so that the amplification is not affected by frequency for values up to several thousand kilocycles per second. Usually, however, the amplification is given as the ratio of the output power to the input power, and the effect of the reactance due to electrode capacities depends on the kind of circuit that is used. If the reactance of the output circuit has the effect of capacity, or if the output circuit consists of a resistance, the input resistance is positive. Under such conditions, power is taken by the tube from the input circuit. The value of this power which is used is so small at ordinary frequencies that it may be neglected. At high frequencies no power is taken by the grid circuit, but the electrode capacities offer a path to the input current and thus reduce the amplification.

The increase in effective interelectrode capacity may become so large under certain load conditions as to affect the performance of the tube at high audio frequencies. Thus, in a resistance-coupled amplifier the effective capacity reaches a value of 250 to 300 micromicrofarads, which is high enough to cause a decrease in amplification at frequencies over 5,000 cycles per second.

In general, then, it may be said that the effect of interelectrode capacity is to produce a coupling between the input and output circuits. Consequently the tube does not have a true unilateral or single-direction characteristic. The extent of the coupling depends upon the circuit constants. This coupling may cause a feed-back of energy to the input circuit, or, with certain circuit adjustments, an absorption of energy from the input circuit. The effect of interelectrode capacity is to reduce amplification at high frequencies. Several schemes for decreasing this effect are given in a later section (page 182).

Screen-grid or Four-element Vacuum Tube.—The screen-grid vacuum tube may be represented diagrammatically as in Fig. 51. The conventional method of indicating a vacuum

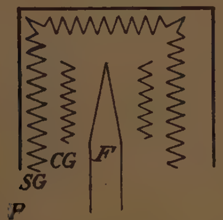


FIG. 51.—Diagrammatic representation of screen-grid vacuum tube.

FIG. 52.—Conventional representation of screen-grid vaccum tube.

tube of this kind is given in Fig. 52. The filament is shown at *F*, the control grid at *CG*, the screen grid at *SG*, and the plate at *P*. If the plate of the tube is disconnected and the screen grid is used as the plate electrode, the operation of the tube is no different from that of a three-element tube. The screen-grid tube is intended for use as a radio-frequency amplifier and is then connected with a positive voltage on the screen grid by means of a tap from the "B" battery. The construction is such that the plate gets the necessary number of electrons even though there is a screen grid in the tube.

It has been explained that the tuning of the input circuit of a tube is dependent to some extent upon the adjustments of the plate circuit, because of the effect of the input capacity. Further, the mutual capacity of the grid-filament condenser and the plate-filament condenser may produce "feed-back."

Several circuit arrangements have been devised to be used with ordinary tubes to counteract or neutralize this effect.

The screen-grid tube avoids the necessity of such circuit arrangements because it is constructed in such a way that voltage variations in the plate circuit cannot affect the grid-filament circuit. This permits a considerable increase in the possible voltage amplification of the tube. The screen grid, although connected to the "B" battery which is shunted by a large condenser to a ground wire, is, in effect, at ground potential with respect to radio-frequency currents. Hence, the control grid is shielded from any plate voltage variations by the screen grid.

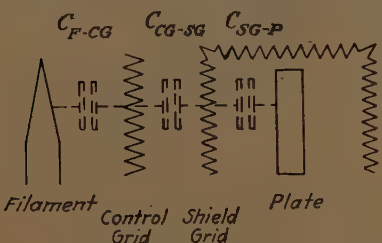


FIG. 53.—Diagram of electrode capacities of screen-grid vaccum tube.

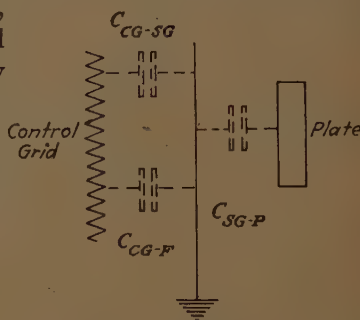


FIG. 54.—Diagram of capacity effect between control grid and plate of screen-grid vaccum tube.

The electrode capacities of the screen-grid vacuum tube may be shown as in Fig. 53 in which the dotted lines indicate the equivalent capacities. Thus $C_{F\text{-}CG}$ is the capacity of the condenser action between the filament and the control grid. The capacity between the control grid and the plate, as shown in Fig. 54, is made up of two parts; that is, the capacity between the plate and the ground, and the capacity between the screen grid and the control grid. The latter in turn consists of the two capacities indicated in the drawing. Thus the capacity between the control grid and the plate is reduced materially, having a value of a few hundredths of a micro-microfarad, because the resultant capacity of two capacities in series is smaller in value than either of the components.

Although the internal capacity between the control grid and the plate is small, it has been found that neutralization of the

radio-frequency amplifying tubes seems necessary when a screen-grid tube is used in the radio-frequency stages of a circuit using regeneration applied to the radio-frequency transformer.

Shielding of Screen-grid Circuits.—The internal shield of a screen-grid tube prevents or greatly minimizes feed-back through the interelectrode capacities of the tube. This, however, is only one form of coupling between stages. If there is any *magnetic* feed-back from one tuning circuit to the preceding one, there is a tendency for oscillation to take place in the circuit. Hence, it is necessary, also, to shield the input from the output circuit. The amount of shielding depends upon the voltage amplification per stage and the design of the circuit. A metallic shield for each tuned stage usually is sufficient. If the voltage amplification is high, it may be necessary to use on the tube a grounded metal covering extending to the base.

Voltage Amplification of Screen-grid Tube.—In the operating range, changes of plate voltage do not cause appreciable variations in plate current because of the screening effect of the second grid. Consequently, the amplitude of changes of plate current produced when the voltage of a radio signal is impressed on the grid is affected very little by an increase in load resistance. For this reason, the use of a very high resistance or impedance in the plate circuit is advantageous in order to obtain high voltage amplification.

The voltage amplification is determined by the mutual conductance of the tube and by the load impedance. The mutual conductance gives the amplitude of changes in plate current due to the application of the voltage of a radio signal to the control grid. The output load voltage is directly proportional to the load impedance because with an increase in impedance there is practically no change in amplitude of the signal current. The voltage amplification of a tube which has a mutual conductance of 350 micromhos or 0.00035 mho and which is used with a load impedance of 100,000 ohms is 100,000 $\times$ 0.00035 or 35 per stage.

When properly used as a radio-frequency amplifier, the screen-grid tube gives a voltage amplification per stage of 25

to 50 in the broadcast range as compared with 5 to 12 per stage with the three-element tube.

Figure 55 shows the stage amplification curve of a UX-222 tube, which has a tuned circuit connected to its plate. The stage amplification is taken as the ratio of E_2 to E_1 where E_2 is the voltage developed across the plate load and E_1 is the input voltage. The constants of the tube at the "operating point" for this curve are r_p = 810,000 and u = 285. An increase in

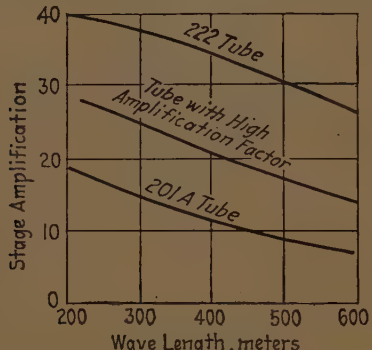


FIG. 55.—Relation of stage amplification to wave-length for three types of tubes.

the plate resistance r_p above 200,000 ohms is not of much advantage so far as amplification is concerned, because it becomes more difficult to couple the circuit to the tube in order to obtain the best voltage transfer.

Figure 55 also shows the stage amplification of a tube with a high-amplification factor (u) of, say, 50 and a plate resistance of 85,000 ohms, as well as that of a UX-201A tube when operated at u = 8.6 and r_p = 9,500 ohms. In each case the selectivity of the circuit which was used with the tube was adjusted for the same value.

CHAPTER V

REACTIVATION OF VACUUM TUBES

Reactivation of Thoriated Tungsten Filaments.—The action of the thorium-oxide layer on the thoriated tungsten filament of a vacuum tube is such that, when the filament is heated, some of the thorium oxide is reduced to metallic thorium and works out to the surface of the filament. When the vacuum tube is in use, this surface layer of thorium gradually evaporates and is replaced at the same rate by fresh thorium from the interior of the filament. This process continues uniformly throughout the life of the tube provided the normal temperature of the filament is not exceeded. If the temperature is raised a few hundred degrees above the normal temperature, corresponding to a voltage overload of about 10 per cent of the rated value, the balance between surface evaporation of thorium and its supply is disturbed and the active thorium layer is completely evaporated, leaving a plain tungsten surface from which the *filament emission* rapidly decreases. If the operator further increases the filament voltage, the overload on the tube is increased so much that no filament emission is obtained. The filament then is "paralyzed" but can be restored by *reactivation.*

Only tubes with thoriated-tungsten filaments can be reactivated. In the following types of vacuum tubes thoriated-tungsten filaments are used: UX-199, UX-120, UX-200A. UX-201A, UX-222, UX-240, UX-171, and UX-210. In the following "UX" types thoriated-tungsten filaments are not used: 11, 12, 112, 171A, 200, 226, 227, 280, and 281. The filaments of the latter group of tubes cannot be reactivated and would be burned out by the application of the high voltage used in the process. Information as to the type of filament used in a tube is given on the data sheet placed in the tube package or may be obtained from the manufacturer.

Need for Reactivation. Emission Test.—An indication of the condition of a vacuum tube for filament emission is readily obtained by an *emission test.* In the test for filament emission described on page 91 the current for producing filament emission is set at a certain low value and the condition of the filament is determined by the value of filament voltage which is needed to produce the required amount of emission.

The data of an emission test which was made with the apparatus described on page 91, is given in the following table.

EMISSION TEST CONDITIONS OF VACUUM TUBES

Type of tube	Filament, volts	Plate, volts	Minimum emission, milliamperes
UX-199	3.3	50	6
UX-120	3.3	50	15
UX-210A	5.0	50	25
UX-200A	5.0	50	12
UX-240	5.0	50	25
UX-171	5.0	50	50
UX-210	6.0	100	100
UX-213	4.0	100	50 per filament
UX-216B	6.0	125	100

Voltages higher than those given in the table must not be used because of the danger of damaging or possibly even burning out the tube. If the value of emission current indicated on the milliammeter in this test is above the minimum value specified in the table, the tube filament is in good condition and reactivation is not necessary.

The value of plate current, when the tube is operated at rated voltages, is not an accurate measure of filament condition. The reason for this is that small variations in the constants of the tube (especially the amplification factor) cause much greater variations in the plate current, even though the performance of the tube is not appreciably affected. If, however, the plate current reading is low, and increases rapidly as the filament voltage is increased slightly above the rated value, it is likely that the filament is becoming inactive.

If the plate current reading of a used tube is less than 80 per cent of the reading when the tube was new (provided the operating voltages in each test are the same), improvement will result from reactivation.

If a test of the emission current after the tube has been reactivated does not show an increase in value, the filament has come to the end of its normal life, the supply of thorium has become exhausted from the effect of overload, or the vacuum in the tube has deteriorated. Tubes with poor vacuum will show a filament current reading which is greater than the rated value. If the vacuum is very poor the filament will not light unless the filament voltage is increased considerably above normal—then it will momentarily light up and burn out.

Tubes in which the elements are short-circuited cannot be reactivated. It is advisable to test for this condition before reactivation is attempted. The "shorts" testing method described on page 89 may be used.

If an operator finds that his tubes need reactivating frequently, say every month, it is likely that they are being overloaded. Overloading or improper operating conditions may be due to the use of (1) filament voltages greater than the rated values for the tubes, (2) high plate voltages without the use of a "C" battery, (3) reversed "A" or "C" battery connections, (4) inactive tubes in use together with good ones.

Tube Life.—Most standard vacuum tubes are designed to deliver their rated output throughout the normal life if operated at the specified voltages. A life of 500 hours represents the usage of a tube in average service for 1 year. Performance of this kind can be secured only from tubes which are not abused or overloaded. The use of a filament voltmeter ensures proper filament voltages and is conducive to an increase in tube life and a saving in battery current.

Methods of Reactivating.—The kind and degree of overload which has been put upon a tube determines the method to be used in reactivating the filament.

First Method.—Tube filaments which have been overloaded only slightly may be reactivated by a simple process. Accord-

ing to this treatment the filament is burned at the voltage given in the following table. During this treatment no voltage is applied to the grid or plate of the tube.

Type of Tube	Burning Voltage, Volts
UX-199	4
UX-120	4
UX-222	4
UX-201A	7
UX-201B	7
UX-200A	7
UX-240	7
UX-171	7
UX-210	9
UX-213	6
UX-216B	9

The filament is burned at the voltage specified in the table for 30 minutes and then an emission test (page 91) is made. If the value of emission current is not above the specified minimum, the filament must be burned again. The length of time necessary for reactivation by this method ranges from 0.5 to 1.5 hours. If the emission shows no improvement after the filament has been burned for about an hour, it is evidence that the tube has been overloaded heavily over a long period of time. In such a case, the second method of reactivation, as described below, should be tried.

Second Method.—According to the second method the filament is first "flashed" at the following voltage for 10 to 20 seconds. During the "flashing" of the filament no voltage is applied to the grid or plate.

This treatment accelerates the rate at which the thorium works out of the interior of the filament to the surface. Since there is no voltage on the grid or plate, the evaporation of thorium from the filament surface is slow.

The filament is burned for a period of 30 minutes at the burning voltage given in the first method of reactivation as already described. If the emission current shows no improvement at the end of this period, the burning should be continued,

making an emission test after each ½ hour. If the emission current is unsatisfactory after a burning treatment of 2 hours, the tube cannot be reactivated.

Type of Tube	Flashing Voltage, Volts
UX-199	12
UX-120	12
UX-222	12
UX-210A	16
UX-201B	16
UX-200A	16
UX-240	16
UX-171	16
UX-210	16
UX-213	16
UX-216B	16

The high temperature developed in flashing is necessary to "strip" or clean the filament surface. After this step, which, in effect, completely paralyzes the filament, the burning voltage is applied in order to form another layer of fresh thorium on the filament surface. It is possible to reactivate a tube filament in as short a period as 10 minutes by using voltages higher than those in the table above. This treatment, however, has a very injurious effect upon the life of the tube and the improvement is only temporary. It must be expected that a small percentage of tube filaments will burn out when the flashing voltage is applied. The number of burn-outs is increased considerably when higher voltages are used in reactivating.

The curves in Fig. 56 are the result of a test made on the reactivation of a 3-volt filament. They show the relation between emission and time of treatment for three voltages: 3.5 volts, 4.0 volts, and 5.0 volts. Curve I indicates the effect of treatment at 3.5 volts; the emission was restored rather slowly and finally reached a value not much over the minimum. Curve II indicates the effect of treatment at 5.0 volts; here the emission was restored very rapidly at first, but then fell much below the specified minimum. Curve III indicates

the effect of 4.0 volts; this shows a reasonable rate of restoration and a high final value. It is apparent from these curves that the recommended reactivation voltages should be used for best results.

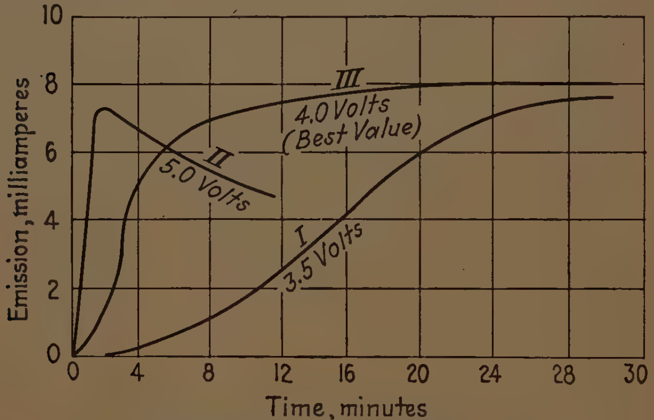


FIG. 56.—Emission curves for reactivation of filament.

Equipment for Reactivating Tubes.—An arrangement for reactivation in which storage batteries can be used is shown in Fig. 57, the connections being made only to the filament terminals of the socket. The voltmeter is very essential as an aid in securing the correct value of applied voltage. The storage battery intended for flashing must be kept charged and, to reduce the current drain, only one tube should be flashed at a time.

LIST OF APPARATUS FOR DIRECT CURRENT EQUIPMENT

1 "A" storage battery, 4 volts.
1 "A" storage battery, 12 volts.
1 "B" storage battery, 24 volts, 6,000 milliampere-hour capacity.
1 Rheostat, 10 ohms.
1 Voltmeter.
2 Tube sockets.

A very convenient arrangement of a similar apparatus which is operated by alternating current from the lighting supply circuit is shown in Fig. 58. If the transformer in this equipment is to be used for both flashing and burning purposes, it

must have some provision for adjusting the secondary voltage[1] from about 14 to 18 volts, or else two transformers are required, one with a secondary giving about 14 volts, and

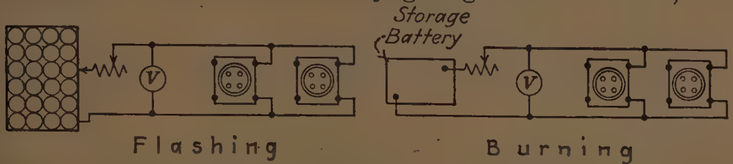


FIG. 57.—Apparatus using battery current for flashing and burning tube filaments.

another giving about 18 volts. The alternating-current voltmeter takes an appreciable current and should remain in the circuit, in parallel with the tube, all the time during reactivation.

LIST OF APPARATUS FOR ALTERNATING CURRENT EQUIPMENT

1 Transformer, 110-volt primary, secondary adjustable from 14 to 18 volts.
1 Rheostat, 30 ohms.
1 Voltmeter, for alternating current.
2 Tube sockets.

Some standard types of tube rejuvenators are not provided with voltmeters for indicating the voltage applied to the filament. Many of these are designed to give an excessive voltage

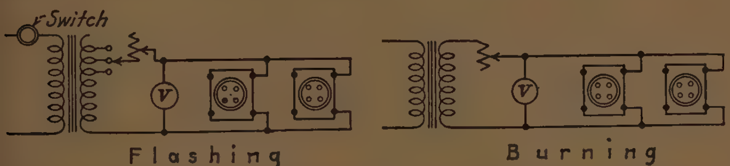


FIG. 58.—Apparatus using alternating current for flashing and burning tube filaments.

and under such conditions of reactivation the tube filament may be so damaged that the injury is permanent or that its life is shortened considerably.

[1] NOTE: A toy or bell-ringing transformer is satisfactory. The General Electric transformer, type 236093, has a secondary with 2-volt taps from 4 to 22 volts.

CHAPTER VI

TESTING VACUUM TUBES

Tube Testing for Service Work.—Simple tests only are ordinarily necessary to determine the condition of a vacuum tube. In the past much was said about the selection of a tube for a particular duty in a radio receiver. This was due mostly to the fact that in the early days of tube manufacturing there was a noticeable variation in the performance of individual tubes, and no special-purpose tubes were available. The characteristics of standard tubes of approved makes are now uniform enough so that the rated values suffice for all usual tube computations.

It is common practice to regard the value of the plate current of a tube as a test of the performance of a tube. This practice, however, gives an exaggerated view of any variation which may be present in the tube. The following data, to illustrate this point, were obtained from a test on a number of Cunningham tubes, type 301A (R.C.A. UX-201A). These tubes were selected on the basis of approximately equal mutual conductances. When operated with a suitable load resistance these tubes gave nearly identical outputs as amplifiers. The following table shows the results obtained.

The plate currents varied from 1.73 to 2.08 milliamperes. If the amplification factors of the tubes had been equal, those tubes having the highest mutual conductances would have shown the highest output. Although this is not indicated, it is interesting to note that the range of variation was approximately the same. For a range of variation of 2.7 per cent in mutual conductance the range in power output was only slightly greater, being 4.9 per cent. The range of 17.3 per cent in the variation of plate current was, however, much greater, but the tube having the lowest plate current was one of those with the highest power output.

Mutual conductance, micromhos	Plate current from battery, milliamperes	Power output, alternating current, milliwatts
656	1.73	16.3
655	1.79	16.3
660	1.85	15.9
656	1.85	15.5
663	1.86	16.1
659	1.89	15.9
657	1.95	16.1
655	2.00	15.5
673	2.08	15.6
658	2.08	15.9
Range of variation, 2.7 per cent	Range of variation, 17.3 per cent	Range of variation, 4.9 per cent

This shows that plate current readings only do not give much information as to the performance of which a tube is capable under operating conditions. If a low plate current reading is due to poor emission of the filament, the tube will show unsatisfactory performance. This condition may be detected more readily by an emission test than by observations of plate current.

Service Tests.—Occasionally a tube is found which has some objectionable feature such as "shorted" elements, "open" filament, poor emission, excessive gas pressure, or inadequate action as an amplifier. In most cases it is safe to assume that a tube will give satisfactory service if it does not have any of these faults. A service test, therefore, should consist of an examination for

1. Tube elements in contact.
2. Closed filament circuit.
3. Filament emission.
4. Presence of excessive gas.
5. Electrical leakage.
6. Operation as amplifier.

Testing Equipment.—It is obvious that a complete check on the performance of a vacuum tube as suggested above requires

NORMAL LIMITS OF OPERATION FOR VACUUM TUBES

Type (UX)	11–12	199	120	201A	200A	240	112	112A	171	210	226	227	213	216B	280	281
I_f, amperes	0.230 to 0.270	0.059 to 0.067	0.124 to 0.139	0.235 to 0.265	0.235 to 0.265	0.235 to 0.265	0.445 to 0.545	0.220 to 0.280	0.470 to 0.530	1.15 to 1.35	0.95 to 1.15	1.40 to 2.10	1.8 to 2.2	1.15 to 1.35	1.75 to 2.25	1.05 to 1.45
I_p, minimum milliamperes	1.8	1.4	4.5	1.3	......	....	4.5	4.5	13.0	11.0	3.5	1.5	65	90	85	115
u, minimum	5.6	5.6	2.9	6.7	15.0	23.0	7.0	7.0	2.6	6.7	7.0	6.8				
r_p, maximum ohms	22,000	22,000	8,500	17,000	37,000	110,000	7,700	7,700	2,500	6,500	11,000	16,000				
G_m, minimum	325	325	425	550	......	275	1,200	1,200	1,150	1,350	800	600				
I_s, minimum milliamperes	6.0	5.5	13.0	20.0	14.0	14.0	45	.....	40	85	35	35	40	85	100	200

Use the voltages below in the test for I_f, I_p, u, r_p, and G_m

E_f	1.1	3.3	3.3	5.0	5.0	5.0	5.0	5.0	5.0	7.5	1.5	2.5	5.0	7.5	5.0	7.5
E_g	−4.5	−4.5	−22.5	−4.5	0	−1.5	−9.0	−9.0	−40.5	−35	−9.0	−6.0				
E_p	90	90	135	90	45	135	135	135	180	425	135	90	40	100	40	100

Use the voltages below in the test for emission I_s

E_f	1.1	3.3	3.3	5.0	5.0	5.0	5.0	See Note[2]	5.0	6.0	1.5	2.5	4.0	6.0	5.0	7.5
$E_{(p+g)}$[1]	50	50	50	50	50	50	50		50	100	50	50	100	125	80	150

[1] $E_{(p+g)}$ indicates that the voltage is applied to the plate and grid connected together. The emission current is the total current flowing to both elements. It is read on a milliammeter connected in the common lead.

[2] Emission readings cannot be taken on type UX-112A.

the use of an elaborate testing set. The simpler outfits, however, in their limited field are just as useful as the larger ones. In the following section, six types of testing sets are described. For the convenience of those who wish to construct such equipment there is included, for each testing set, a wiring diagram and list of materials. The range of readings for normal tube operation is given in the preceding table.

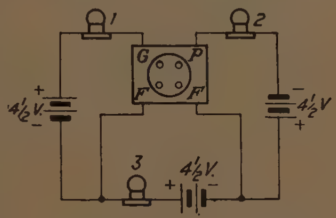


FIG. 59.—Testing set for short circuits, tube elements and continuity of filament circuit.

Testing Set Number 1.—This consists of a simple arrangement which will indicate whether the filament circuit is closed or open, and whether or not the elements are in contact. The wiring diagram is shown in Fig. 59.

LIST OF EQUIPMENT

3 "C" batteries, 4½ volts each.
3 Mazda miniature lamps, 6.0 volt, 0.1 ampere type.
3 Sockets for minature lamps.
1 UX type tube socket.
1 Adapter or socket for bases of other types of tubes.
1 Panel and cabinet for mounting.

Method of Operation.—The tube to be tested is put into the socket. If lamp 3 lights and lamps 1 and 2 do not light, the filament circuit is closed. If lamp 1 lights, there is a short circuit between the filament and the grid. If lamp 2 lights, there is a short circuit between the filament and the plate. If lamps 1 and 2 light, there is a short circuit between the grid and the plate.

Testing Set Number 2.—This is an arrangement used in a tube "checker" that is in common use. This set depends upon a reading of plate current to indicate the condition of the tube. The wiring diagram is shown in Fig. 60.

LIST OF EQUIPMENT

1 "B" battery, 45 volts.
1 "A" battery, 6 volts, or 4 dry cells.

1 Milliammeter, 0 to 15 milliamperes.
1 Voltmeter, 0 to 7 volts.
1 Single-pole double-throw switch (push button type is convenient).
1 Rheostat, 0 to 50 ohms, ½ ampere capacity.
1 UX type tube socket.
1 Adapter or socket for bases of other types of tubes.
1 Protective lamp type C-377.
1 Auto lamp socket, double-contact.
1 Panel and cabinet for mounting.

The protective lamp is used to protect the milliammeter from being burned out if a short-circuited tube is put into the socket of the testing set.

Method of Operation.—The rheostat is first adjusted to show the rated filament voltage on the voltmeter. Then the tube to be tested is put in the test socket. If the filament circuit is open, there is no change in the reading E_f on the voltmeter as the tube is inserted. The reading E_f drops to a value lower than usual when a tube with an air leak is encountered. The next step is to adjust the rheostat again until the voltmeter shows the rated filament voltage. Then throw the switch to one pole, read the value of plate current I_p as shown on the milliammeter, reverse the switch, and again read the value of plate current. The result of reversing the switch is to change the polarity on the grid. A difference between the two plate current readings indicates that the tube is operating. The extent of the difference is a measure of the mutual conductance of the tube.

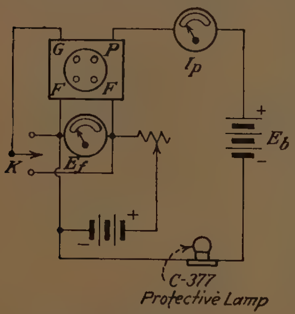


FIG. 60.—Plate current testing set.

Testing Set Number 3.—This is an arrangement designed to give a check on emission and plate current. It is necessary to remember that the exact value of plate current is not of much importance (unless the variation from the average value is great), provided the emission is adequate. The wiring diagram is shown in Fig. 61

List of Equipment

1 "B" battery, 45 volts.
1 "B" battery, 22½ volts.
1 "A" battery, 6 volts.
1 "C" battery, 3 volts or 4½ volts with tap.
1 Milliammeter, 0 to 10 milliamperes
1 Voltmeter, 0 to 7 volts.
1 Switch, double-pole double-throw (the telephone key type is convenient).
1 Rheostat, 7 ohms, 1.5 ampere capacity.
1 Rheostat, 20 ohms, ¾ ampere capacity.
1 Rheostat, 50 ohms.
1 UX type tube socket.
1 Adapter or socket for bases of other types of tubes.
1 Protective lamp C-377 and socket.
1 Panel and cabinet for mounting.

Note: The three rheostats are to be connected in series.

Method of Operation.—The three filament rheostats are to be adjusted to give the maximum resistance and then the tube to be tested is put into the test socket. When the switch K is moved downward, the milliammeter is in the grid circuit. In this position there is a negative voltage of 3 volts on the plate of the tube. Then the filament rheostat is adjusted carefully until the milliammeter indicates a value for emission I_s of 3.0 or 5.0 milliamperes depending upon the type of tube in the socket. The reading of the voltmeter indicates the value of filament voltage E_f which is needed to cause the emission I_s. The limiting values of E_f for good tubes are given in the table below.

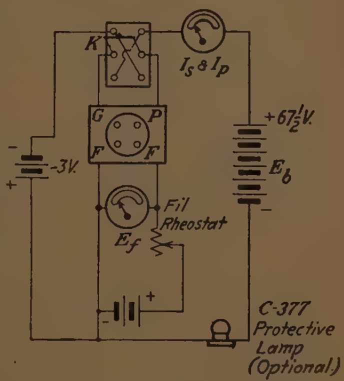


Fig. 61.—Emission testing set.

When the switch K is moved upward, the milliammeter is in the plate circuit and the negative voltage of 3 volts is on the grid. Then the filament rheostat is adjusted until the voltmeter indicates the rated value of filament voltage for the tube

in the socket. The milliammeter indicates the value of plate current I_p.

A new tube which is low in emission may be defective because of the presence of too much gas. A used tube which is low in emission generally has been operated at a filament voltage, or a plate voltage, or both, considerably over the rated value. The table below gives the allowable range of the value of I_p for various tubes.

Type	Emission test		Plate current test	
	I_s, milli-amperes	E_f, volts	E_f, volts	I_p, milli-amperes
11–12	3.0	1.0	1.1	1 to 5
199	3.0	2.8	3.3	1 to 4
120	3.0	2.9	3.3	4 to 10
201A	5.0	3.9	5.0	1 to 4
240	5.0	3.9	5.0[1]	0.1 to 1
112	5.0	3.5	5.0	2 to 8
112A	5.0	3.5	5.0	2 to 8
171	5.0	3.7	5.0[2]	5 to 15
226	5.0	1.0	1.5	2 to 8
227[3]	...	...	2.5	1 to 6

[1] For type UX-240 reduce the bias to zero.

[2] For type UX-171 reduce the plate voltage to 45.

[3] For type UX-227 the emission may be checked by the method given on p. 95. The emission limits which apply here are shown in the table on p. 88.

Testing Set Number 4.—This is an arrangement which is designed for use on an alternating-current circuit of 110 volts, 60 cycles. It gives a check on short-circuited elements, open or closed filament circuits, filament emission, and operation of the tube as an amplifier. The wiring diagram is shown in Fig. 62.

The two rheostats required are to be connected in series. The bell-ringing transformer is used to step-down the applied voltage of the power circuit, and the potentiometer serves as a control of the input voltage to the testing set. The output transformer is needed to step-down the output to the crystal

and milliammeter indicator. Two other types of output circuits are shown in Fig. 62. The C-377 protective lamp prevents high-emission tubes from damaging the milliammeter. The two miniature lamps are used as indicators of short-circuited tube elements.

List of Equipment

2 "B" batteries, 45 volts each.
1 "A" battery, 6 volts.
1 "C" battery, tapped at 1½, 4½, and 16½ volts.
1 "C" battery, 4½ volts.
1 Voltmeter, 0 to 7 volts.
1 Milliammeter, 0 to 50 milliamperes.
1 Milliammeter, 0 to 1.5 milliamperes.
1 Switch, double-pole double-throw (key type).
1 Rheostat, 6 ohms, 2 ampere capacity.
1 Rheostat, 50 ohms, ¼ ampere capacity.
1 Bell-ringing transformer, 110 volt primary, 12- to 18-volt secondary, 60 cycles.
1 Potentiometer, 400 ohms.
1 Output transformer (a "B" eliminator transformer will do).
1 Crystal rectifier, heavy duty carborundum type (a dry chemical rectifier from a battery charger will do).
1 Protective lamp, C-377, and socket.
2 Mazda miniature lamps, 6 volts, 0.1 ampere.
2 Sockets for miniature lamps.
2 UX type tube sockets.
2 Adapters (or sockets added in parallel) for bases of other type of tubes.
1 Panel and cabinet for mounting.

Method of Operation.—The tube to be tested is put into the socket used for the short-circuit test. If lamp 1 lights, there is a short circuit between the filament and the grid. If lamp 2 lights, there is a short circuit between the filament and the plate. If both lamps light, there is contact between the filament and both the grid and the plate or there is contact between the grid and the plate.

After the short-circuit test, the tube is put in the alternating-current test socket, the rheostat is adjusted until the voltmeter indicates the rated value of filament voltage E_f, and the switch is closed to the *right*. In this case, the grid and the plate are connected together and the emission current

I_s is read on the milliammeter. Next, the switch is thrown to the *left*. This puts an alternating voltage in the grid-to-filament circuit. The value of the transformed and rectified plate current is read from the output milliammeter in the output circuit.

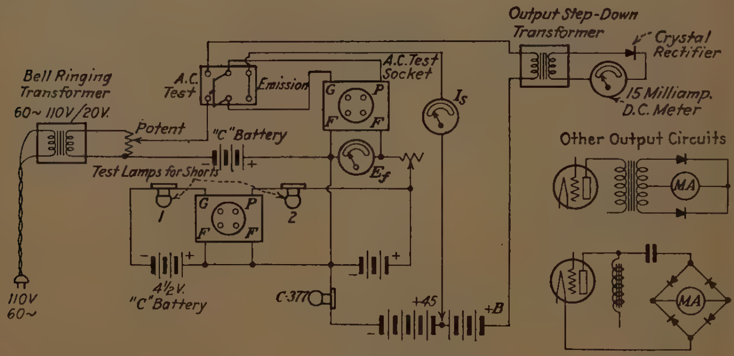


FIG. 62.—Tube testing set for use with alternating current supply.

The recommended value of "B" and "C" voltages should be used. If a "B" voltage of 90 is used, the grid-bias voltage should be adjusted as follows for various types of tubes:

Type (UX)............	199	120	201A	240	112	171
Grid bias (volts).......	4½	16½	4½	1½	4½	16½

Testing Set Number 5.—This is an arrangement designed for use as a complete testing set. It gives a check on short-circuited elements, filament emission, plate current, pressure of gas, and operation of the tube as an amplifier. The wiring diagram is shown in Fig. 63.

The two rheostats, for filament voltage adjustment, are connected in series. The potentiometer is used to adjust the "B" battery voltage. The single-pole double-throw switch is needed to put the grid leak in or out of the circuit. The three-point switch is required for bias-voltage variation. The miniature lamps are placed in the circuit in such a manner that they will indicate short-circuited elements.

LIST OF EQUIPMENT

2 "B" batteries, 45 volts each.
1 "A" battery, 6 volts.

1 "C" battery, tapped for 1½, 4½, and 16½ volts.
2 "C" batteries, 4½ volts each.
1 Voltmeter, 0 to 150 volts.
1 Voltmeter, 0 to 8 volts.
1 Milliammeter, 0 to 50 milliamperes.
1 Milliammeter, 0 to 15 milliamperes.
1 Milliammeter, 0 to 800 milliamperes.
2 Switches, double-pole double-throw (key type).
1 Switch arm, with three contact points.
1 Switch, single-pole double-throw.
1 Rheostat, 6 ohms, 2 ampere capacity.
1 Rheostat, 50 ohms, ¼ ampere capacity.
1 Potentiometer, 200 ohms.
2 Mazda miniature lamps.
2 Sockets for miniature lamps.
1 Grid leak, 1.0 megohm, and holder.
1 UX type tube socket.
1 Adapter or socket for bases of other types of tubes.
1 Panel and cabinet for mounting.

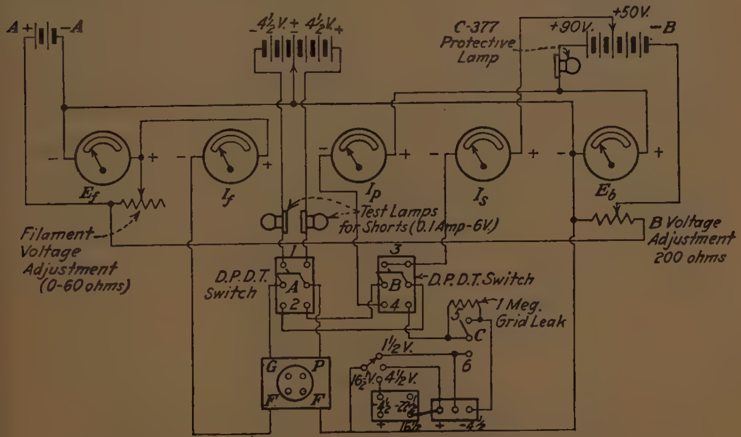


FIG. 63.—Complete tube testing set using battery current.

Method of Operation.—After the tube to be tested has been put into the socket, the rheostat is adjusted until the filament voltmeter indicates the rated value of filament voltage E_f. If the filament circuit is open, there is no indication of filament current I_f on the filament milliammeter. With switch A in position 1 and switch B open, a short circuit between the tube elements will cause the test lamps to light.

The emission test is made by closing switch A to position 2 and switch B to position 3. The value of the emission current I_s is indicated on the milliammeter. A check on the plate current is obtained by closing switch B to position 4. The value of the plate current I_p is indicated on the milliammeter.

The test for excessive gas or electrical leakage depends upon the change in plate current resulting from the insertion of a high resistance into the grid circuit. The settings made in the previous test are not changed. Switch C is closed to position 5 and the reading of plate current I_p is noted. Then switch C is opened and the plate current reading is noted again. Excessive gas or electrical leakage is indicated by a change in plate current greater than 0.1 milliampere.

A check on the operation of the tube as an amplifier is obtained from a comparison of mutual conductances. The settings of switches A and B are not changed. Switch C is closed to position 6, and the plate current reading is noted. If this reading differs from the reading obtained above when switch C was in position 5, the tube is in a good operating condition. For convenience, a summary of the switch positions for the tests is given below.

Position switch			Test
A	B	C	
1	open	5	Shorted elements
2	3	5	Emission
2	4	5	Plate current
2	4	open	Excessive gas and leakage
2	4	6	Mutual conductance

Testing Set Number 6.—This is an inexpensive arrangement designed for testing power and rectifier tubes. It gives a check on the condition of the filament and the emission current. The wiring diagram is given in Fig. 64.

List of Equipment

2 "B" batteries, 45 volts each.
1 "A" storage battery, 6 volts.
1 Fixed resistance unit, ½ ohm, 2 amperes capacity.
2 Lamps, 110 volts, 10 watts each.
1 UX type tube socket.
1 Panel and cabinet for mounting.

Method of Operation.—The tube to be tested is first put into the socket. If the tube lights, its filament is intact. In this connection it should be noted that type UX-213 tube is made with two filaments. Tubes with oxide-coated filaments, such as types UX-280 and 281, show only a dull glow when the filaments are lighted.

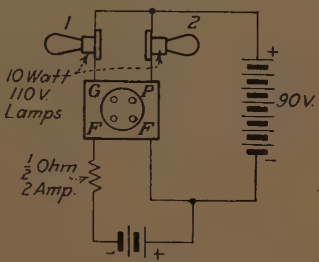


Fig. 64.—Testing set for power tubes.

The intensity of the brilliancy of the light of lamps 1 and 2 is taken as a measure of the filament emission. Of course, short-circuited elements would make these lamps light brightly so the tube may be tested first for short circuits in testing set number 1. The color indications for tubes in good condition are as follows:

Type (UX)	Lamp number	
	1	2
210	dull red	dull orange
213	dull orange	dull orange
216B	dark	dull orange
280	dull orange	dull orange
281	dark	dull orange

Methods for Measuring Tube Characteristics.—A study of the characteristics of a vacuum tube is of considerable importance in determining the manner in which a tube can be used for best results. Several devices for obtaining these characteristics are in use. From the *characteristic curves* obtained

with these devices it is possible to get the values of such fundamental characteristics as *mutual conductance*, *amplification factor*, and *plate resistance*.

The first part of this section deals with the finding of the so-called "static" characteristics, meaning the relations which are possible between voltages and currents when there is no load in the plate circuit and a direct-current grid bias is used. It should be remembered that the relations which actually exist between voltages and currents, when the tube is operating in any of its applications, are determined by the characteristics of the radio apparatus used with the tube as well as by the characteristics of the tube itself. Those relations which are called the *dynamic characteristics* are treated in a later section.

Equipment.—A thorough understanding of the action of a vacuum tube is suggested as the best way to become familiar with methods of testing. The various testing methods in themselves become quite simple if viewed in the light of what the function of a vacuum tube is and how it is used. A conveniently satisfactory testing set must, of course, include the necessary instruments for obtaining the data needed. The *testing set* shown in Fig. 65 has five instruments mounted beneath the panel.[1] The filament voltmeter for measuring filament-to-grid voltage has a scale of 0 to 6 volts which is a sufficient range for the radio receiving tubes now commonly used. The ammeter for measuring the current for heating the filament usually has a range of from 0 to 1.25 amperes, which is satisfactory for the usual values of current. The filament-to-plate voltmeter should have a range of from 0 to 180 volts, which will take care of the highest plate voltage ordinarily used. The milliammeter for observing the plate-to-filament current should have a scale for reading up to 10 milliamperes; and while, under certain conditions, power tubes which have more than 90 volts impressed on the plate-to-filament circuit may carry a current which is beyond this range, the full-scale value of 10 milliamperes has been chosen so that readings at

[1] This testing instrument is made by the Jewell Electrical Instrument Co., Chicago, Ill.

the low part of the scale may be made with sufficient accuracy. Ordinary vacuum tubes when in service in a receiving set should never take as much as 10 milliamperes in the filament-to-plate circuit, so that the higher values which have been mentioned here are of interest only in experimental work on special types of tubes.

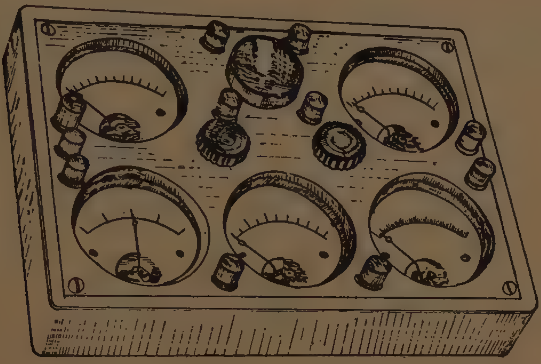


FIG. 65.—Testing set (on panel) for vacuum tube characteristics.

In series with the plate-to-filament milliammeter there should be a resistance of about 300 ohms which serves in a measure to protect the milliammeter in case a tube that has a grounded plate should be placed in the socket of the testing set. This value of resistance is sufficiently low so that it will not introduce any appreciable error in the determination of the plate resistance which is usually more than 10,000 ohms for ordinary tubes. It is of sufficiently high value, however, to prevent burning out the milliammeter under ordinary conditions.[1]

[1] For routine tests a 10-watt tungsten-filament lamp may be placed in series with the "B" battery which is required for the operation of the testing set, and the battery circuit should then be equipped with a short-circuiting switch. If the reading of the plate-to-filament voltage does not change appreciably when the vacuum tube is placed in the socket, the tungsten lamps can be short-circuited as in such case the plate of the vacuum tube is not likely to be grounded. On the other hand, if the plate-to-filament voltage drops to zero when the tube is inserted, its plate is probably grounded and the lamp will protect the instruments.

The voltmeter of the testing set for measuring the grid-to-filament voltage should have a scale of from 0 to 10 volts on each side of a central zero, so that both positive and negative voltages may be applied and measured in the filament-to-grid circuit. For power-tube work a range of 0 to 40 volts on each side is necessary.

A vacuum tube socket for the insertion of tubes should be mounted in the testing set. When tubes having other than standard bases are to be tested, an adapter may be used, or, four short wires may be attached to the four marked binding posts around the socket and connected to a suitable base or socket which is outside the group of instruments included in the testing set.

Battery Connections of Testing Set.—The various instruments of a testing set for vacuum tubes may be connected together, as shown in Fig. 66. Binding posts are shown at the right-hand side for connecting the "A" battery. The current from the "A" battery goes through an ammeter and then through a 60-ohm rheostat which has the right amount of resistance for UX-199 tubes with 6 volts applied to the filament of the tube in the test set when all of the resistance of the rheostat is used. It is also suitable for testing tubes which require as much as 1 ampere when not much of the resistance of the rheostat is used. The "A" battery circuit is then completed through the tube by way of the socket and back to the battery. The "filament" voltmeter is connected directly across the filament terminals of the socket. The terminals for the "B" battery are the two on the bottom edge of the set, and the plate voltmeter is also connected to these terminals. The negative side of the "B" battery is connected to the negative side of the "A" battery. The current from the positive side of the "B" battery goes through the milliammeter, which measures the plate current, and then to the plate terminal of the base or socket of the tube. If a

When a great many tubes are to be tested, a foot switch may be arranged to short-circuit the lamp. In this way, a large number of tubes can be tested rapidly with the minimum possibility of damage to the plate-to-filament milliammeter.

great many tests are being made, it is desirable to use storage "B" batteries since a large amount of current is used under some conditions of testing.

The three left-hand binding posts of the testing set shown in the figure are connected to two 10-volt batteries or to any source which will give from 0 to 10 volts from the center to each side. The center left-hand terminal should be connected to the center of the group of cells, connecting the upper binding

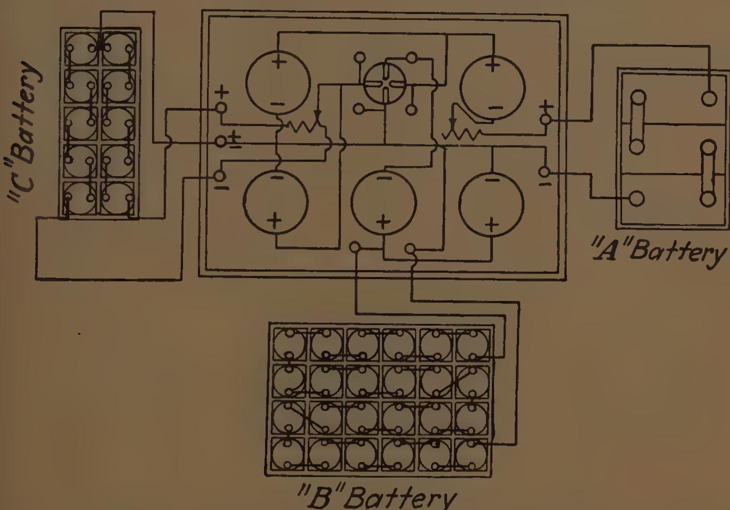


FIG. 66.—Diagram of testing set for tube characteristics showing connected batteries.

post to the five cells toward the positive terminal (from the previous connection) and the lower terminal to the five cells toward the negative side. A storage battery is recommended for this work, also, in preference to dry cells, since for continuous testing the current drain is considerable.

With the set properly connected to the batteries, as explained above, the best way to become familiar with the method of testing is actually to take the complete characteristics of several vacuum tubes. The following characteristics are those taken from a UX-201A tube, and it is

suggested, for a first test, that a tube of this type be used, as it will follow the characteristics given more closely.

Operating a Test.—Before placing the tube in the testing set, turn the left-hand knob until the grid voltmeter is at the middle of its scale or at zero. Then the right-hand knob should be turned until the filament voltmeter has no deflection from zero. The vacuum tube is to be put into its socket and the knob of the right-hand rheostat is to be turned clockwise. This will have the effect of raising the voltage across the tube as will be indicated on the filament voltmeter. The voltage should be raised gradually until it indicates the normal value of filament voltage for the tube that is being tested.

Filament current can be read on the right-hand ammeter and for the UX-201A tube should be 0.25 ampere or fairly close to this value. Many vacuum tubes made by so-called "independent" manufacturers will require higher values of current and will show a considerably higher battery drain than when the best makes of tubes are used. Under these conditions there will probably be a flow of current through the tube between the plate and the filament as indicated on the plate milliammeter. This is the current which passes through the primary of an audio-frequency transformer or through the telephone receivers or the loud speaker.

Plate Current-grid Voltage Curve.—As already stated, one of the primary functions of a vacuum tube is to show a large change in plate current for a small change in the grid voltage. The grid voltage is varied by turning the left-hand knob of the testing set. It will be noted that as the indicating needle of the grid voltmeter goes toward the left-hand (negative) side the amount of current indicated on the plate milliammeter becomes less, and as the needle of the grid voltmeter goes toward the right (positive) the plate milliammeter increases its reading. Since the quality of a tube depends upon the ratio of the change in plate current to the change in grid voltage, a curve can be plotted between plate current and grid voltage as indicated on the instruments in order to get this value. When the filament excitation is normal and the plate ("B" battery) voltage of the vacuum tube is 45 volts, the

necessary data for this curve are easily obtained. The figures for these data may be written on paper or they may be plotted directly on cross-section paper. The left-hand knob regulates the potentiometer and should be turned until the grid voltmeter indicates sufficiently far to the left (negative) to reduce the reading on the plate milliammeter to zero. This value of grid voltage should be recorded as well as the plate current which is, of course, zero. The next step is to lower the grid voltage gradually toward zero, and then increase it in the opposite direction. For each "even" volt read, the value of plate current is shown in the following table. The following data were obtained from tests of a UX-210A vacuum tube.

Filament voltage.......................... 5.00 volts
Filament current.......................... 0.25 ampere
Plate voltage.......................... 45.00 volts

Grid Volts, Negative	Plate Milliamperes
6	0.0
5	0.1
4	0.2
3	0.4
2	0.7
1	1.1
0	1.6
Positive	
1	2.1
2	2.8
3	3.5
4	4.2
5	5.0
6	5.8
7	6.6
8	7.4
9	8.3
10	9.2

Using these values a curve should be plotted on cross-section paper. It will have the shape of curve "45V" in Fig. 3. Information such as the volts and amperes in the filament circuit and the plate voltage, as well as the other data of the test, should be recorded on the curve sheet.

Mutual Conductance.—It was shown, in the explanation of how a vacuum tube operates, that the ratio of changes in plate current to changes in grid voltage (called *mutual conductance*) is a better measure than any other single factor for determining the relative merit of different tubes. A curve, which represents the relation between these two factors with horizontal values (abscissas) for grid voltage and vertical values (ordinates) for plate current, is a graphical device to show the good or poor qualities of vacuum tubes. In the portion of such a curve where it is steep, there is a relatively large change in plate current for a change in grid voltage, and where the curve tends toward a horizontal direction the plate current has a relatively smaller change. The slope of this curve is, therefore, proportional to the mutual conductance and is a measure of the good qualities of the vacuum tube which has been tested.

Since the slope of a curve showing the relation of plate current to grid voltage changes somewhat at different points, the values of mutual conductance should be taken at the point in the curve at which the vacuum tube is to be used. The grid voltage used in making such a curve is measured with respect to the negative end of the filament. If the tube is to be used as an amplifier and the grid return is connected to the negative end of the filament, the slope should be taken at the zero of grid volts. If a 5-volt vacuum tube is used as an amplifier in a receiver with a 6-volt battery supplying the "A" battery current, and the grid return is brought back to the negative end of the rheostat, then a negative grid-bias voltage of about 1 volt with respect to the negative end of the filament is obtained. Under these conditions, the slope should be taken at a grid voltage of minus one (−1). If a grid-biasing battery voltage is to be used, the slope of the curve should be taken at a negative value of grid voltage corresponding to the value of the "biasing"[1] battery.

The slope of a curve showing the variation of plate current with grid voltage at the actual point where the tube is to be

[1] "Biasing" battery is a term used, sometimes, to designate the application of a "C" or grid-bias battery.

used is most easily determined by placing a straight-edge tangent to the curve at the point corresponding to the grid voltage (with respect to the negative end of the filament) and drawing a line intersecting the scales of plate milliamperes and grid volts. It may be assumed, for example, that the grid return is connected to the negative end of the filament and that all values of current will be taken with the grid voltage at zero. In the case shown by Fig. 67, the vertical distance from the line of zero milliamperes to the intersection of the tangent line with the right-hand edge of the curve sheet should be noted, this being 6.8 milliamperes; and then this value is

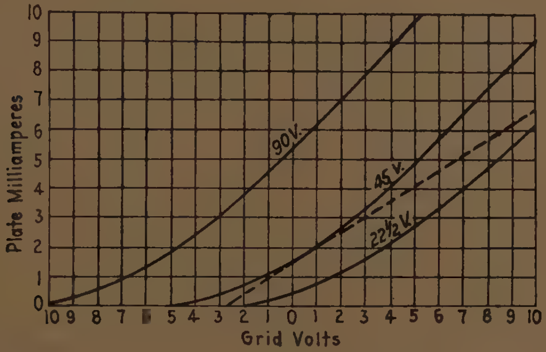


Fig. 67.—Use of tangent to curve of relation between plate current and voltage for obtaining mutual conductance.

to be divided by the distance along the base line from the right (adding positive and negative values) which is 13 volts. The value obtained by this division is 0.52 which is the slope of this line at the point where the tube is actually working and is the value of the *mutual conductance* of the vacuum tube. Its value, however, is not stated in the standard terms ordinarily used. This will be explained in the next paragraph.

Because the values of current are in milliamperes instead of amperes, it is necessary to divide this value of mutual conductance as obtained above by 1,000; and further, because resistances are expressed in micromhos instead of mhos, a multiplying factor of 1,000,000 must be used. The final result is that the above number must be multiplied by (1,000,-

000 ÷ 1,000) or 1,000 to obtain the value of the mutual conductance of the vacuum tube in micromhos. Multiplying 0.52 by 1,000 gives 520 as the mutual conductance in micromhos.

Similar curves should be drawn for other tubes and at other values of "plate" voltage, and the slope of the curve or the mutual conductance taken in order to become familiar with this method of testing. Figure 68 shows a series of curves taken on a UX-199 tube.

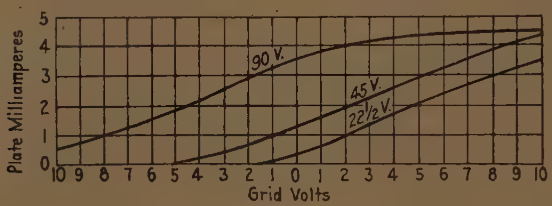


FIG. 68.—Curves of mutual conductance of typical vacuum tubes.

Characteristic Values of Standard Tubes.—The table below gives generally accepted values for the mutual conductance of several standard types of tubes at various plate voltages, together with other constants which will be described later. It must be expected that some tubes will deviate from these values considerably. In general, a variation of 10 to 20 per cent either way from these values should be allowed.

Simplified Method of Finding Mutual Conductance.—The taking of the mutual-conductance values as given above is somewhat tedious when a great many tubes must be tested, although it must be done where the actual curves are desired, as for matching tubes. For rapid testing of tubes, however, a shorter method from which no curves can be made may be worked out which will check the tubes with sufficient accuracy. In the application of this briefer method, the batteries are to be connected as in the method previously described, the tube is to be placed in the socket provided for it, and its filament voltage is to be adjusted to the standard value. The grid voltage is then set at 2.5 volts, negative; that is, to the left of zero. The plate current in milliamperes is then read and recorded. Following this first test, the grid voltage is shifted

to 2.5 volts, positive, and the plate current is again noted. The plate current will be higher for this second reading than for the first reading, the increase being due to the change in grid voltage. The first value of plate current when subtracted from the second value gives the increase in plate current in milliamperes for a 5-volt total change in grid voltage, and when the change in plate current in milliamperes is multiplied by 200,[1] the value of mutual conductance in micromhos will be obtained. This method is not quite so exact as the method used when the curve is taken, but is sufficiently accurate for most commercial testing.

As an example of this method a UX-201A vacuum tube was tested at a plate voltage of 45 volts. At 2.5 volts negative, or to the left of zero on the grid voltmeter, the plate current was 0.6 milliampere. At 2.5 volts positive, the plate current was 3.2 milliamperes. This is an increase of 2.6 milliamperes and two hundred times this value gives 520 which checks with the mutual conductance obtained from the curve. To sum up, the simplified method of getting the mutual conductance is to set the grid voltmeter at 2.5 volts negative, and observe the plate current, then set the grid voltmeter 2.5 volts positive, observe the increase in plate current over the previous reading, multiply by 200, and the result is the mutual conductance in micromhos.

Matching Tubes by Mutual-conductance Tests.—The question of matching tubes for the more complicated receiving sets requires considerable attention under certain conditions. It applies particularly to amplification where the tube capacity and impedance play an important part. The two radio-frequency tubes in a neutrodyne or other tuned radio-frequency set and the intermediate-frequency amplifiers in a superheterodyne may be matched to each other. Some improvement will be shown with the use of matched tubes as against tubes picked at random.

The proper method of matching tubes is to obtain a curve showing the relation of the plate current to the grid voltage

[1] This multiplication factor of 200 as used here is the value of the ratio 1,000/5 or multiplier/grid-voltage range.

AVERAGE CHARACTERISTICS OF VACUUM TUBES

Tube	Use	"A" battery supply, volts	Filament terminal, volts	Filament current, amperes	Detector "B" voltage, volts	Amplifier "B" voltage, volts	Negative "C" voltage, volts	Plate current at highest "C" voltage, milliamperes	Plate resistance, ohms	Mutual conductance, micromhos	Voltage amplification factor
WD-11 or WX-12....	Detector amplifier	1.5	1.1	0.25	22.5	45	0–1.5	1.1	18,000	340	6.5
						67.5	0–3.0	1.8	17,000	360	
						90	4.5	2.6	16,000	430	
UV or UX 199......	Detector amplifier	3.0	3.3	0.063	22.5	45	0.5–1.5	1.0	19,500	320	6.25
		to			to	67.5	1.5–3.0	1.7	16,500	380	
		4.5			45	90	4.5	2.5	15,000	415	
UX-120...	Power amplifier	4.5	3.3	0.132		90	16.5	3.2	7,700	428	3.3
						135	22.5	7.0	6,600	500	
UX-201A.	Detector amplifier	6.0	5.0	0.25	45	45	0.5–1.5	0.9	18,500	430	8.0
						67.5	1.5–3.0	1.7	14,000	570	
						90	4.5	2.0	10,000	725	
						135	9.0	2.5	10,500	760	
UX-200A.	Special detector	6.0	5.0	0.25	45	.....	....	1.0	30,000	670	20
UX-240...	Detector high-*u* amplifier	6.0	5.0	0.25	90	90	1.5	0.2	150,000	200	30
						135	3.0	0.2	150,000	200	
						180	4.5	0.2	150,000	200	
UX-112A..........	Power amplifier	6.0	5.0	0.25	45	90	4.5	4.8	5,300	1,500	8.0
						135	9.0	5.8	5,000	1,600	
						157	10.5	7.9	4,700	1,700	
						180	13.5	7.8	4,700	1,700	
UX-171...........	Power amplifier	6.0	5.0	0.50	....	90	16.5	11.0	2,500	1,200	3.0
						135	27.0	16.0	2,200	1,360	
						157	33.0	18.0	2,150	1,400	

UX-226............	Amplifier	A.C.	1.5	1.05	....	180	40.5	20.0	2,000	1,500	8.2
						90	6.0	3.7	9,400	870	
						135	12.0	3.0	10,000	820	
						180	16.5	3.8	9,400	870	
UY-227............	Detector amplifier	A.C.	2.5	1.75	45	90	6.0	3.0	11,300	725	8.2
						135	9.0	5.0	10,000	820	
						180	13.5	6.0	9,400	870	
UX-210............	Power amplifier oscillator	8.0 or 7.5 A.C.	7.5	1.25	....	180	12.0	7.0	7,000	1,100	7.7
						250	18.0	12.0	5,600	1,330	
						350	27.0	16.0	5,100	1,500	
						425	35.0	18.5	5,000	1,550	
UX-250............	Power amplifier	8.0	7.5	1.25	....	250	45.0	28	2,100	1,800	3.8
						350	63.0	45	1,900	2,000	
						400	70.0	55	1,800	2,100	
UX-213............	Full-wave rectifier	A.C.	5.0	2.0	Max. a.c. voltage plate to filament, 220 per anode			Max. d.c. load current, milliamperes [illegible]			
UX-280............	Full-wave rectifier	A.C.	5.0	2.0	Max. a.c. voltage plate to filament, 300 per anode			Max. d.c. load current, milliamperes 125			
UX-216B...........	Half-wave rectifier	A.C.	7.5	1.25	550			65			
UX-281............	Half-wave rectifier	A.C.	7.5	1.25	700			85			
UX-874............	Voltage regulator	....	Rated voltage, 90 volts d.c.			Starting voltage, 125 volts d.c.			Max. d.c. current, 50 milliamperes		
UX-876............	Ballast tube	....	Current, 1.7 amperes			Voltage range, 40 to 60 volts			Standard Mogul type, screw base		

as explained above, applying the plate voltage which will be used in the receiving set. Those tubes should then be considered as matched which have parallel curves with the same slope and have practically the same position on the curve sheet. An easy way to make this comparison is to hold two or three curve sheets up to the light. Those which coincide represent well-matched tubes. Curves for a quantity of tubes may be placed on individual sheets and matched into groups. The tubes which are difficult to match may be used in other locations. In general, the tubes with the steepest slope should be used as detectors and the others as oscillators. For audio-frequency work, particularly for loud-speaker operation, a tube must have a long, straight characteristic in order to secure uniform reproduction.

Soft tubes[1] which contain a rather small amount of gas will frequently have irregular curves. Such tubes are quite generally used as detectors, because they have greater sensitivity than the hard tubes. The reason for this is that they can be used near one of the irregular humps in the curves which are typical of this kind of tube. A detector tube which gives a very irregular curve will quite frequently show remarkable results when critically adjusted.

The necessary value of negative grid-bias voltage to be used on an amplifier tube when operated with high plate voltages may be determined from mutual-conductance curves. It is always advisable to keep the plate current as low as possible to conserve the plate battery and to reduce external resistance losses. Accordingly, the grid should be made sufficiently negative so that the tube is operating on the lowest part of the straight-line slope of the curve. Curves may be taken at higher voltages, and this value of negative grid bias is then determined from the curve instead of by direct experiment.

The mutual conductance may be determined, also, from the ratio of amplification constant to plate resistance; the result is given in micromhos if the ratio is multiplied by 1,000,000.

[1] A *soft* tube is intended to require adjustment of voltage to suit the service for which it is used. A *hard* tube does not require this adjustment.

Amplification Factor.—The next important constant of a vacuum tube is the amplification factor. This is defined as the ratio of the change in plate voltage (which is necessary to change the plate current a given amount) to the change of grid voltage (which will produce the same variation in the plate current). The amplification factor u does not change much in value over the range of operating voltages. It undergoes a small and usually negligible decrease in value at low plate voltages. The amplification factor is useful for determining the qualities of a vacuum tube as an amplifier. Values of amplification factors of standard tubes are given on page 108. This factor can be obtained from a curve showing the variation of plate current with grid voltage by taking a reading, preferably on the straight-line slope of the curve, at some slightly different value of plate voltage from that used for making the curve. This point should be plotted on the cross-section paper in its proper position with reference to grid voltage and plate current for this new value of plate voltage. For example, on the enlarged portion of the curve (Fig. 69), the point P is the new value which was taken at a plate voltage of 35 volts. The original curve was taken at 45 volts. Hence, the change in plate voltage is 10 volts, the grid remaining at zero voltage with respect to the negative end of the filament. As shown in the figure, the value of plate current drops from 1.60 to 0.95 milliampere, a difference or change of 0.65 milliampere.

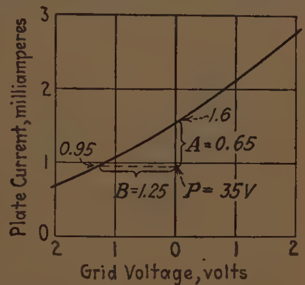


FIG. 69.—Curve of relation of plate current to grid voltage to determine amplification factor.

From the above definition the amplification factor is equal to the change in plate voltage divided by the change in grid voltage. The grid voltage which would be necessary to produce this same change in plate current is the horizontal value from the point P to the curve which is marked by the distance B, in this case, 1.25 volts. The amplification factor of this tube under these conditions is then 10 divided by 1.25, or 8.0.

It should be noted that the above value is an average for operating conditions between 35 and 45 volts. To get this result more accurately, it is necessary that the change in plate voltage should be very much smaller than the values taken above, but this greater accuracy is scarcely worth while in routine tests, as the values obtained by the method that has been described will be found to check very closely with the values obtained by standardization laboratories with very elaborate equipment.

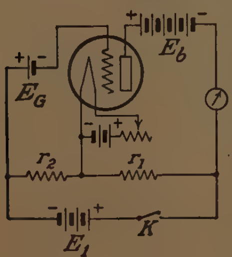


FIG. 70.—Simple apparatus for measuring amplification factor.

Another method of measuring amplification factor is shown in Fig. 70. The equipment required is a 10-ohm fixed resistance r_2, a calibrated variable resistance r_1 (up to 400 ohms for tubes having an amplification factor up to 40), and a key K. When the key K is open, the tube is in the normal operating condition, r_1 being too small to have much effect on plate current. When K is closed, the battery E_1 of about 10 volts discharges through r_2 and r_1. The voltage divides between r_2 and r_1 in proportion to the values of their resistances. The voltage across r_2 is applied to the grid in the reverse direction to that impressed on the plate due to the drop across r_1 in the plate circuit. The voltage on the grid is amplified by the tube and produces a voltage u times as great in the plate circuit. This voltage tends to change the plate current, but it is offset by the portion of the voltage across r_1. If these opposing voltages do not balance, a small change in plate current results. By closing K and increasing or decreasing r_1, a setting is found at which no change in plate current occurs. Then r_1 is u times r_2 and the amplification factor $u = r_1/r_2$. If r_2 is 10 ohms, it is only necessary to divide r_1 by 10 to obtain the value of the amplification factor.

It is equally satisfactory to introduce opposing voltages into the grid and plate circuits, varying one until the plate current returns to its original value, and then determine the ratio between them. If a 1-volt change in grid voltage is made, the plate current is affected to an extent equal to that produced by

a plate voltage u times as great. If the grid voltage is then left fixed and the plate voltage varied until the plate current is again at the initial value, the change in plate voltage is equal to u. Thus, when a UX-201A tube is operated at the rated filament voltage, with 90 volts on the plate and -4.5 volts on the grid, the plate current is 2.05 milliamperes. If the grid voltage is then increased to -5.5 volts, the plate current drops to 1.50 milliamperes. When the plate current is restored to the original value by increasing the plate voltage to 98.2 volts, the change is 8.2 volts. Since the change in grid voltage is 1 volt, this change in plate voltage is a measure of the amplification factor, and $u = 8.2$.

Plate Resistance.—The term "plate resistance," as explained before (p. 66), does not apply to the resistance offered to the flow of a direct current in the plate circuit, but is the resistance offered to the flow of an alternating current in such a circuit. The resistance offered to the flow of a direct current may be considered as the internal or direct-current resistance of the tube.

The plate resistance may be obtained from the values already found as it is simply the ratio of the change in plate voltage to the change in plate current. The change in plate voltage for the conditions on page 111 was 45 minus 35, or 10; the change in plate current was 1.60 minus 0.95 milliamperes, or 0.65 milliampere, or 0.00065 ampere, this value being shown as the distance A on the curve in Fig. 69. The ratio of 10 to 0.00065 is 15,400, which is the plate resistance.

Another method of determining plate resistance is from the ratio of plate voltage change to the corresponding plate-current change. In Fig. 71 the variation of plate current with changes of plate voltage for a UX-201A tube is shown. If a plate voltage of 45 volts is applied, the plate current at the point A is 1.70 milliamperes or 0.0017 ampere. The internal or direct-current resistance of the tube is equal to the reciprocal of the slope of the line connecting this point with the origin O. This *direct-current resistance* R may be computed from the current and voltage readings, as follows,

$$R = \frac{45}{0.0017} = 27{,}280 \text{ ohms.}$$

At the point B, with an applied voltage of 90 volts and a current of 6.0 milliamperes, the resistance is lower, being 15,000 ohms.

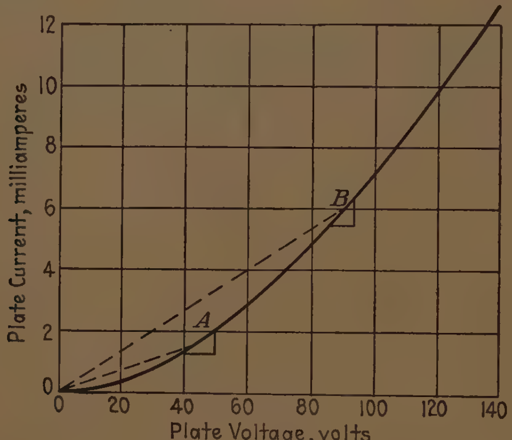


FIG. 71.—Variation of plate current with plate voltage for UX-201A tube.

The *plate resistance* may be determined from the curve showing the relation between plate voltage and plate current by computing the slope of a tangent to the curve drawn through the point in question. For example, the tangent

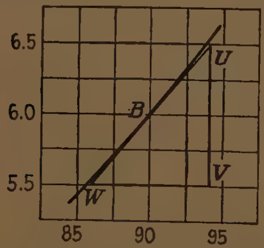


FIG. 72.—Curve for determining plate resistance for plate voltage of 90 volts.

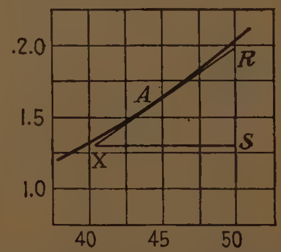


FIG. 73.—Curve for determining plate resistance for plate voltage of 45 volts.

UW at the point B may be drawn as shown on the enlarged section of the curve in Fig. 72 and the triangle UVW constructed. Then WV represents the change in plate voltage dE_p and VU the corresponding change in plate current dI_p.

From these values the plate resistance r_p may be computed. The plate voltage $dE_p = 94 - 86$ or 8 volts. The plate current $dI_p = 6.50 - 5.50 = 1.0$ milliampere $= 0.001$ ampere, and the plate resistance, $r_p = dE_p/dI_p = 8/0.001 = 8{,}000$ ohms. Similarly, the plate resistance at 45 volts (point A, Fig. 73) is 15,740 ohms.

These values are roughly one-half of the direct-current resistance of the tube, which is 15,000 ohms at 90 volts. Similarly, the readings at 45 volts are 27,280 and 15,740, respectively. An estimate of the alternating-current "plate resistance" can be obtained by reading the plate current and plate voltage, computing the direct-current resistance from these readings, and taking one-half of this value.

The plate resistance may also be determined from two sets of instrument readings. In this case, the grid voltage is left fixed, and the plate-current reading is taken with the plate voltage set a few volts below the value of plate voltage at which the plate resistance is desired. The voltage is then increased an equal amount above the nominal value of plate voltage and both sets of readings recorded. From these readings the plate resistance may be computed. Referring to Fig. 72, the readings are taken at points opposite W and U. When E_p is 94 volts, $I_p = 65.5$ milliamperes or 0.00655 ampere. When E_p is 86 volts, $I_p = 5.55$ milliamperes or 0.00555 ampere, and

$$r_p = \frac{94 - 86}{0.00655 - 0.00555} = \frac{8}{0.0010} = 8{,}000 \text{ ohms.}$$

In addition to the curve shown in Fig. 71 and the values which were taken from it, curves may also be made from the following data: The variation of filament current I_f with filament voltage E_f. The variation of plate current I_p with filament voltage E_f. The variation of plate current I_p with filament current I_f. The variation of plate current I_p with plate voltage E_p.

These values are self-explanatory and when plotted will show the operation of any tube and will make it possible to visualize the operation better than by any other method.

Grid Resistance.—Another characteristic which is useful in a study of a vacuum tube is the grid resistance or grid conductance, sometimes called the "input resistance" or "input conductance." This measures the alternating current flowing in the grid circuit for a given value of applied alternating voltage. The method of obtaining this is shown on the enlarged portion of the curve showing the variation of grid current with grid voltage in Fig. 74. If an alternating voltage with an amplitude of 0.25 volts is impressed on the steady grid voltage of -0.4 volts at the point O on the curve, the total voltage will vary between R and S and the current between U and T. The tangent to the curve at O coincides closely with the curve in that region. Now the conductance g is the ratio of maximum current to maximum voltage and hence $g = UR/OR =$ slope of tangent. Hence, the conductance for small variations about a point on the curve is equal to the slope of the tangent to the curve at that point and the resistance is equal to the reciprocal of the slope. The value of mutual conductance is obtained more accurately from the ratio WV/WO.

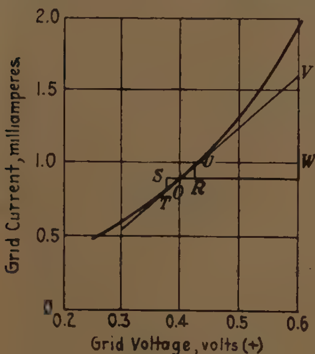


Fig. 74.—Curve for obtaining input conductance.

Numerically,

$$g = \frac{.72 \times 10^{-1}}{.2} = 3.6 \times 10^{-6} \text{ mhos.}$$

$$R = \frac{1}{g} = 2.8 \times 10^{5} \text{ ohms.}$$

The conductance decreases and the resistance increases as the angle the tangent makes with the horizontal is reduced. That is, if the positive value of the steady grid voltage is decreased, the input resistance increases, or the value of an alternating current in the grid circuit is decreased, for a given alternating voltage applied to the grid. In order to keep the input power small, it is desirable to make the grid resistance

high by setting the steady grid voltage at zero or even making it negative.

Plate Conductance.—Still another important characteristic called the *plate conductance* is obtained from a curve showing the relation of plate current to plate voltage. This curve shows how the plate current varies with plate voltage when the grid voltage is constant. The plate conductance at any point is equal to the slope of this curve at that point. The plate resistance is equal to the reciprocal of the plate conductance. These quantities measure the alternating current in the plate circuit for a given applied plate voltage when there is no appreciable external resistance or reactance in the circuit.

Values of Tube Constants to Be Used.—A tube with low-impedance and high-amplification factor will give greater signal strength in either a radio- or an audio-frequency amplifier. The low-impedance tube, however, will cause the radio-frequency amplifier to oscillate; and will require a "C" battery when used in an audio-frequency amplifier. In some highly compensated sets it is imperative that a tube having a low-impedance and a high-amplification factor be used in the radio-frequency stage. If a receiving set has a decided tendency to oscillate, the use of the high-impedance tubes in the radio stages will stop the oscillation and smooth out the tone qualities. If a receiving set will not get distant signals, it may be worth while to try tubes of low-impedance values but with high-amplification factors. The selection of tubes for audio-frequency use is not as critical as for radio frequency. Detector tubes should have average or "medium" impedances and amplification factors.

Dynamic Characteristics.—Under certain conditions the "dynamic" characteristics of a tube are of more fundamental importance than the static values. To obtain such data it is necessary to apply an alternating potential to the grid of the tube and to make use of certain balanced-bridge measurements.

One type[1] of bridge (Fig. 75) has been developed to provide for the measurement of filament emission and certain so-called

[1] General Radio bridge type 361A.

"static" characteristics, and to act as a direct-reading bridge giving three fundamental "dynamic characteristics" of the tube, namely: the amplification factor, the plate resistance, and the mutual conductance. To measure these dynamic constants the bridge must be supplied with current from an audio-frequency tone source,[1] preferably sinusoidal in character, and then be balanced for a zero setting in the telephone head-set. All changes in the bridge to obtain the different

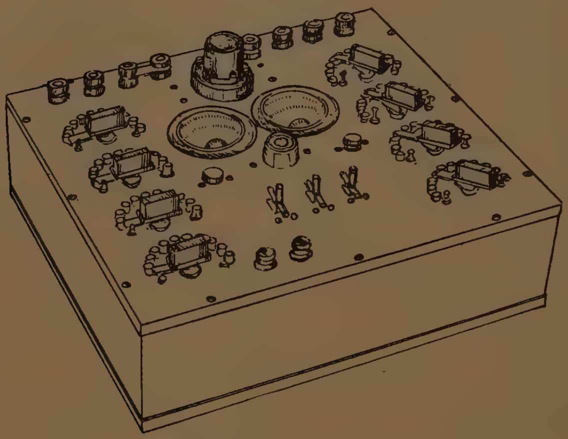


Fig. 75.—Apparatus for determining "static" and "dynamic" characteristics of vacuum tubes.

circuits used are made by means of throw switches. The balancing adjustments are on a dial decade scheme. The tube to be measured is inserted in a detachable UX type socket, mounted externally on the panel of the bridge, and fitted with an adapter for the small base tubes such as the UX-199. A 10-volt meter is provided for measuring the voltage directly across the filament terminals and, by means of a multiplier, the "B"-battery voltage. A 5-milliampere meter is used for measuring the plate current. This is equipped with a shunt

[1] The General Radio type 213 tuning fork oscillator may be used for this purpose.

extending its range to 25 milliamperes. Provision is made for inserting any desired "C" battery in the grid circuit. Thus, by varying the filament voltage, plate voltage, and grid-bias voltage (by means external to the bridge) the data for the customary "static" characteristic curves may be read conveniently on the bridge meters.

The bridge is equipped with three telephone keys and two four-dial resistance arms, the proper manipulation of which enables the operator to determine quickly the three "dynamic" characteristics mentioned above for any particular specifications of filament voltage, plate voltage, and grid-bias voltage. Thus, in a similar manner, the "dynamic" characteristic curves of a particular tube may be easily and rapidly obtained and research or routine inspection work greatly facilitated. With special equipment the bridge may be used to measure alternating-current tubes also.

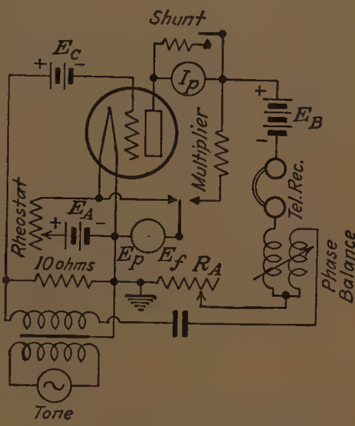


FIG. 76.—Diagram of connections for direct determination of amplification factor.

The resistances are of the non-inductive low distributed-capacity type, and the bridge is adequately shielded. The input transformer has a shield between its two windings.

The units constituting the bridge may be arranged in any of the accompanying circuits by manipulation of the key switches.

The circuit of Fig. 76, obtained by throwing in the key marked "amplification factor," provides for the direct measurement of the voltage amplification factor of the tube to be tested. The resistance R_A (the four-dial A arm of the bridge) is adjusted until the drop through it, due to current from the tone source, balances the potential (uE_g) resulting in the plate circuit from the voltage E_g impressed on the grid. Minimum tone in the telephones indicates the balance point.

E_g results from the flow of the current from the tone source through the 10-ohm resistance in series with R_A.

In order for no current to flow,

$$E_p = uE_g = R_A I_T$$

where I_T is the current from the tone source, and uE_g is opposite in phase to $R_A I_T$.

When $E_g = 10I_T$ then

$$u = \frac{R_A}{10}.$$

The resistance R_A is numerically equal to $10u$, and the control of the resistance system is calibrated directly in terms of amplification factor.

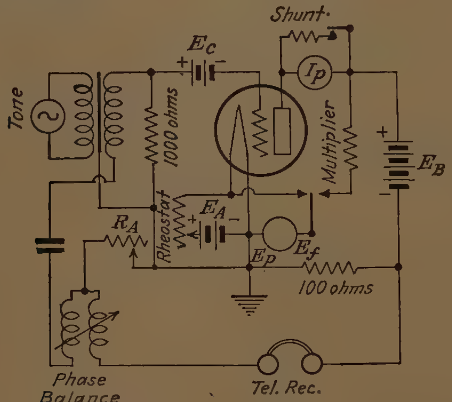


FIG. 77.—Diagram of connections for measuring plate resistance by "bridge" method.

A variometer, by means of which the quadrature component of electromotive force introduced by the tube capacity may be balanced, greatly facilitates the setting. The value may be read to two decimal places. The resistance provides for the measurement of amplification factors up to 100.

To measure the plate resistance r_p, the bridge is set for the circuit of Fig. 77. The value of amplification factor just determined is set on the A arm, and the bridge is balanced by adjusting the four-dial B arm. It will be noted that R_A has been switched to the grid circuit and replaced by the 1,000-ohm

resistance. R_B has been added in the grid circuit. The condition of balance requires that the voltage drops across the 1,000-ohm plate resistance and R_A be equal.

At balance,

$$R_A I_T = 1{,}000 I_p$$
$$I_p = \frac{uEg}{r_p + 1{,}000}$$
$$E_g = I_T(R_B + 10).$$

Substituting and dividing, $R_A = 1{,}000(R_B + 10)u \div (r_p + 1{,}000)$, but $u = R_A/10$, hence $100(R_B + 10) \div (r_p + 1{,}000) = 1$, or $r_p = 100R_B$. R_B is calibrated to indicate the plate resistance directly.

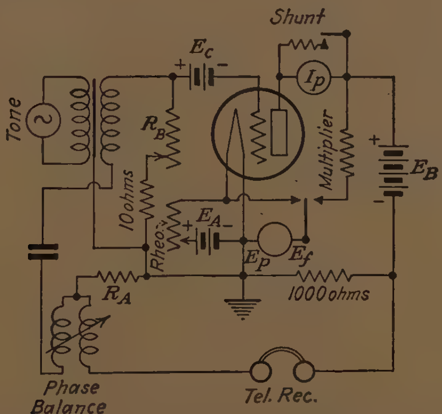


FIG. 78.—Diagram of connections for measuring mutual conductance.

As before, use is made of the variometer in balancing out the quadrature component of electromotive force in accurate adjustments of the bridge. Measurements may be made of plate resistances up to 100,000 ohms in 10-ohm steps.

For a measurement of mutual conductance, the bridge circuit is changed to that of Fig. 78, the 100-ohm plate resistance of Fig. 77 is reduced to 100, and the grid resistance becomes 1,000. A balance is obtained by adjusting R_A and the variometer.

At balance,

$$R_A I_T = 100 I_p = \frac{100 u E_g}{r_p + 100}$$

$$E_g = 1{,}000 I_T$$

$$R_A = \frac{100{,}000u}{r_p} \quad (r_p \text{ is large compared to } 100)$$

$$u = \frac{R_A r_p}{100{,}000}$$

$$\text{Mutual conductance} = \frac{u}{r_p} = \frac{R_A}{100{,}000}.$$

Since the A arm is marked with $\frac{1}{10}$ of its true resistance, the mutual conductance in mhos = reading of A arm $\times 10^{-4}$. Values up to 0.01 mho may be read in steps of one micromho.

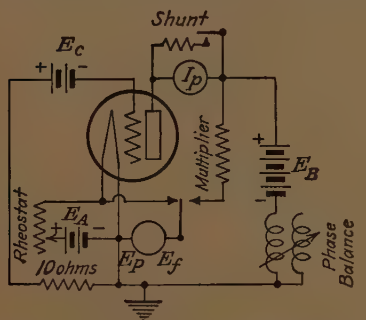


FIG. 79.—Diagram of connections for measuring "static" characteristics.

Figure 79 is the circuit for taking the "static" characteristics. The voltmeter is normally connected across the filament. Depressing a switch connects it across the plate battery, and throws in a multiplier. The maximum reading is 200 volts. The ammeter is provided with a shunt, allowing a maximum reading of 5 or 25 milliamperes. A button type of switch controls the shunt.

Audio Oscillator.—A multitude of bridge measurements require a dependable source of alternating current of low power. The frequency must remain constant. The source of current supply should also be simple in its operation, as well as rugged and reliable. One type[1] of oscillator as shown in Fig. 80 has an output of about 0.06 watt at 1,000 cycles. External binding posts are so arranged that three output voltages may be obtained. The outputs obtainable with these three different connections are as follows:

[1] General Radio type 213.

Position	Voltage	Current
Low.............	0.5 volt	100 milliamperes
Medium..........	1.5 volts	40 milliamperes
High.............	5.0 volts	12 milliamperes

This type can be used for general purposes where a small amount of power of good wave form is required for a single bridge.

For some capacity measurements it is desirable to use a high voltage. This increased voltage may be obtained by connecting an inductance and capacity in series across the high-volt-

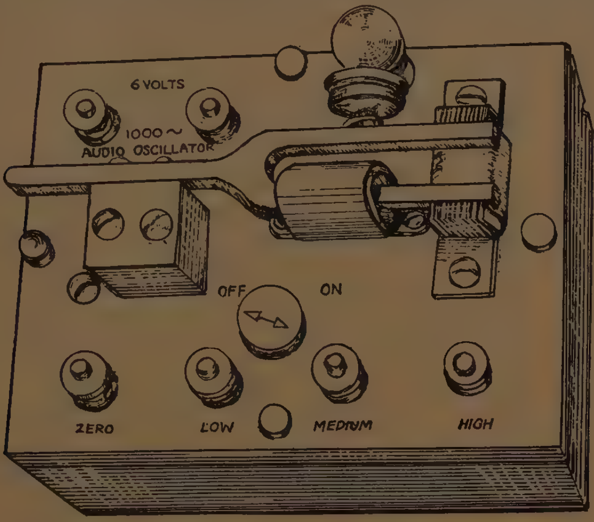


FIG. 80.—Audio oscillator and panel.

age output terminals of the oscillator. By adjusting this circuit to resonance, voltages as high as 50 or 100 volts may be obtained by connecting output leads across the condenser. This instrument will operate satisfactorily on from 4 to 8 volts. The input current is approximately 0.13 ampere. When running, the oscillator may be heard for a distance of approximately 25 feet, or may be made silent by enclosing it in a sound-proof box. The circuit of this oscillator is shown in

Fig. 81. The closing of the switch places the field magnetizing coil directly across the battery. The primary of the input transformer which is in series with the microphone button is also across the battery. The resonance circuit consists of the secondary of the input transformer, the primary of the output transformer, the armature coil, and the condenser. The secondary of the output transformer has three taps to permit the obtaining of three different output voltages. The use of the two transformers prevents the output wave from containing any direct-current components. Each transformer core has a small air gap to prevent distortion of the wave form. Since, however, the magnetic circuits are all nearly closed iron

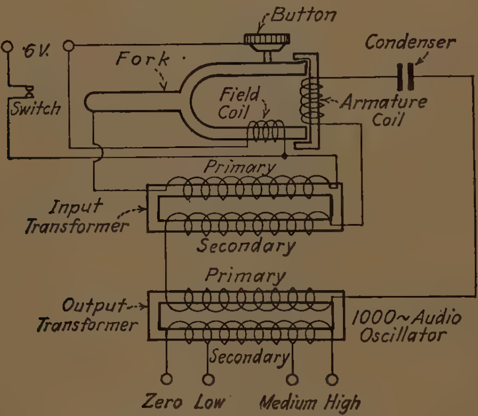


FIG. 81.—Circuit diagram of audio oscillator.

paths there is very little outside field. This feature is particularly important where the oscillator is being used in close proximity to the bridge. The tuning fork in this apparatus makes it possible to keep the frequency constant at 1,000 cycles. The resonance circuit is carefully adjusted to this value. Since the oscillator is self-starting, it may be operated by a switch placed at the bridge, and may be located some distance away from the bridge.

By the use of the field magnetizing coil on one tine or prong of the vibrating fork, instead of relying on its permanent magnetism, the polarity and intensity of the magnetization

of the tuning fork with respect to the armature are permanently maintained.

Success or failure in the operation of an audio-frequency oscillator or "hummer" lies very largely in the microphone button. If the button heats so that the oscillator cannot be run indefinitely, if the adjustment of the button is not permanent, or if slight mechanical shocks change its operating characteristics, the oscillator has little commercial value. A distortion of as small an amount as $\frac{1}{500}$ inch from the normal position of the mica will destroy the perfect operation of the button. In order that the button may be insensitive to mechanical shocks and yet operate properly at 1,000 cycles, use is made of its high inertia effect at the latter frequency. One side of the button is attached to the tuning fork by means of a short, flat spring. The other side, which has a projecting mounting post, is held in position by a specially designed self-centering spring. This combination of springs enables the button to withstand severe shocks, yet it has sufficient inertia so that perfect operation is obtained. The adjustment of the button is permanent. This type of mounting, together with the fact that the electrical constants of the circuits have been adjusted to their best values, insures the continuous operation of the oscillator without heating.

CHAPTER VII

USE OF VACUUM TUBES AS DETECTORS

A vacuum tube, in operation in a radio receiver, is actuated by an alternating current due to the radio signal. The duty of the vacuum tube, as a detector, is to detect and amplify such alternating currents.

An understanding of this action may be gained from a consideration of a vacuum tube of which the curve in Fig. 82

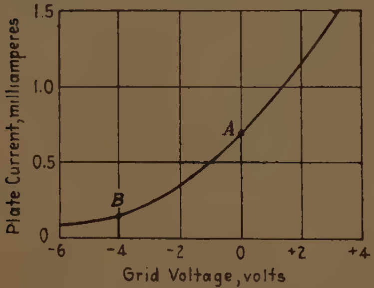


Fig. 82.—Characteristic curve of typical vacuum tube.

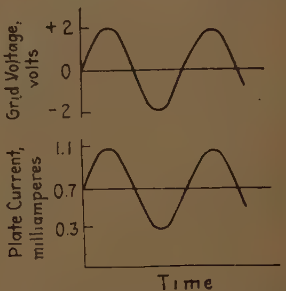


Fig. 83.—Curves of varying grid voltage and plate current for point A in Fig. 82.

shows the relation between plate current and grid voltage. At the zero value of a steady voltage on the grid which corresponds to point *A* on the curve, the plate current is about 0.7 milliampere. Now, if an alternating voltage is applied to the grid of the tube, its voltage will vary above and below the steady value and the plate current will similarly rise and fall. The plate current variations are the same as the grid-voltage variations because the operation of the tube is on the part of the characteristic curve which is nearly straight. At a grid voltage of +2 volts, the plate current is about 1.1 milliamperes and at −2 volts is 0.3 milliampere. These relations are shown in Fig. 83.

The *varying* plate current in Fig. 83 may be considered as consisting of two *components*,[1] one of which is *alternating* and the other of which is *direct* current. The average value of the *varying* current is the same as the value of the *direct* component. The alternating component, in this case, has an amplitude of 0.4 milliampere and an effective value of 0.3 milliampere.

A direct-current ammeter indicates the average value of the current which passes through it, and hence would show no change in the value of the plate current, when the alternating grid voltage is applied.

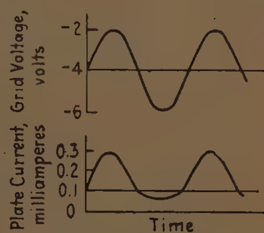


Fig. 84.—Curves of varying grid voltage and plate current for point B in Fig. 82.

Thus if the grid-bias voltage is such that the "point of operation" is on a straight portion of the curve showing the variation of plate current with grid voltage, then the plate current variations are similar to the grid-voltage variations. This illustrates the use of a vacuum tube as an amplifier.

If the same alternating voltage is applied to the grid when operation is at point *B* on the curve (Fig. 82) corresponding to a negative grid voltage of 4 volts, then the grid voltage will fluctuate from -2 to -6 volts. In this case, the plate current corresponding to a grid voltage of -4 volts is about 0.1 milliampere; for -2 volts on the grid it is about 0.3 milliampere; and for -6 volts it is only a little less than the value for -4 volts. These relations are shown in Fig. 84. It is obvious that the curve for the plate current is quite distorted in shape when compared with the curve for the grid voltage. This distortion is due to the fact that the "point of operation" is at the bend of the curve for plate current against grid voltage in Fig. 82. It is evident from this curve (Fig. 84) that the *average* value of the varying current is greater than the *steady* current flowing when no alternating voltage is impressed

[1] A *component* of an alternating electric current is one of the parts out of which the whole may be obtained by the principle of addition of instantaneous values.

on the grid. Under these conditions an ammeter would show an increase in the plate current when the alternating grid voltage is applied. This change in the average value of the current is of importance in the operation of a vacuum tube as a detector.

Purpose of a Detector.—The high-frequency alternating currents used in radio transmission and reception will not flow to any considerable extent through the inductive windings of telephones or loudspeakers. Even if the current did flow, the diaphragms of such apparatus could not vibrate at such high rates; and, further, even if the diaphragms could vibrate at this rate, a note of such high frequency would be inaudible. The detector converts radio-frequency currents, which vary in amplitude at an audio-frequency rate, into pulsating direct currents.

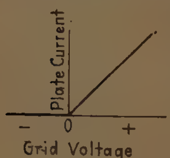


FIG. 85.—Relation between plate current and grid voltage in true detector.

A theoretically *true detector* would operate as shown in Fig. 85. When the grid voltage is positive in value, the plate current varies directly with the voltage, and when the grid voltage is negative the plate current is zero. If, now, an alternating voltage is impressed on such a detector and it is operated at zero grid voltage, a plate current will flow only when the grid voltage has a positive value. With a true detector in a radio receiver, the audio-frequency current is directly proportional to the strength of the radio signal. This action, however, is considerably different from that of the ordinary vacuum-tube detector.

Non-oscillating Tube as Detector without Grid Leak and Condenser.—A circuit illustrating the use of a non-oscillating vacuum tube as a detector with no grid leak or condenser is shown in Fig. 86. The reference point for all voltages is taken as the negative terminal of the filament. The grid return wire is connected to the negative terminal of the "A" battery. The filament rheostat is in the negative leg of the filament. Hence the negative terminal of the "A" battery, and also the grid, is made negative with respect to the reference point at the negative terminal of the filament by an amount equal

to the voltage drop across the rheostat. This negative voltage applied to the grid is called the *grid bias* or *biasing voltage* and fixes the "point of operation" on the curve showing how the plate current varies with the grid voltage. It is obvious that as the voltage of the "A" battery is reduced the amount of grid-bias voltage also decreases. The connection in Fig. 87 provides a constant grid-bias voltage equal to that of the "C" battery. In this case, the rheostat is put in the positive leg of the filament. The connection in Fig. 88 allows the grid-bias voltage to vary from minus to plus; that is, operation can be made to take place at either the lower or the upper bend of the curve in Fig. 82.

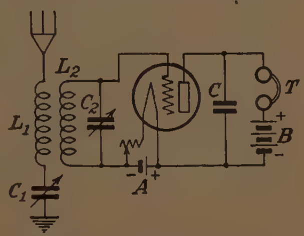


FIG. 86.—Simple circuit including non-oscillating vacuum tube as detector without grid leak and condenser.

Now, when a radio wave from a broadcasting station passes across the antenna of a receiving set, a radio-frequency current is induced in the antenna circuit, which has been tuned to the wave length of the broadcasting station, by the method of varying the capacity C_1 in Fig. 86 until a condition of resonance is obtained. This current produces a voltage drop across

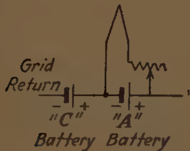


FIG. 87.—Part of circuit in Fig. 86 changed by putting the rheostat in the positive leg of the filament.

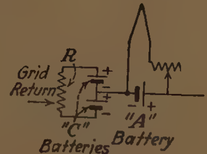


FIG. 88.—Part of circuit in Fig. 86 with variable grid bias.

the coil L_1 which is transferred by induction to the coil L_2. The secondary circuit consisting of L_2 and C_2 is tuned to resonance in order that the voltage across this circuit may be as large as possible. This voltage, which has the same characteristics as the radio wave, is impressed across the vacuum tube between the grid and the filament. It has

already been shown that, when an alternating voltage is applied to the grid under these operating conditions, the wave form of the current in the plate circuit is distorted from that of the grid voltage and that the plate current increases more above the normal value when the grid is positive (relative to the point of operation) than when it is negative.

The average frequency of the waves of sound produced by the human voice in speaking is about 800 cycles per second, but the frequency range varies with the pitch of the tone. A change of inflection in speaking, a change of tone in singing, or in the sound of musical instruments, causes changes in the frequency of the air waves which are produced. In a radio-broadcasting transmitter these air waves are made to modulate the "carrier" oscillations. That is, the radio-frequency oscillations of the *carrier wave*[1] are varied in *amplitude* at the audio-frequency or tone rate of the sound in the microphone. Such modulated radio-frequency currents finally produce radio waves which have the same characteristics as the corresponding sound waves. The radio wave is changed by the radio receiver into sound waves having the same characteristics as the sound waves which entered the microphone at the transmitter. The detection of voice-modulated continuous oscillations is illustrated in Fig. 89. The radio-frequency component of the plate current flows through the by-pass condenser C in Fig. 86, and the pulsating audio-frequency component flows through a telephone receiver or a loudspeaker.

In the action which has been described, detection results from the distortion due to operation on the bend of the curve in Fig. 82 showing the variation of the plate current with grid voltage. This method is sometimes called *detection by plate rectification*, or *detection with grid bias*, or *detection without grid leak and grid condenser*.

An *advantage of the plate rectification* method of detection is that no current flows in the grid circuit because the average value of the grid voltage is maintained negative with respect to the filament in order to operate on the curved portion of

[1] A carrier wave is a radio wave which can be modulated by sound waves.

the curve. Hence, no power is taken from the tuning circuits and no damping effect is exerted on them. This, however, is offset by the necessity of using a "C" battery.

For radio signals of ordinary intensity, the mean value of the change of plate current is nearly proportional to the square of the amplitude of the oscillations of the grid voltage, although the relation does not hold for strong radio signals.

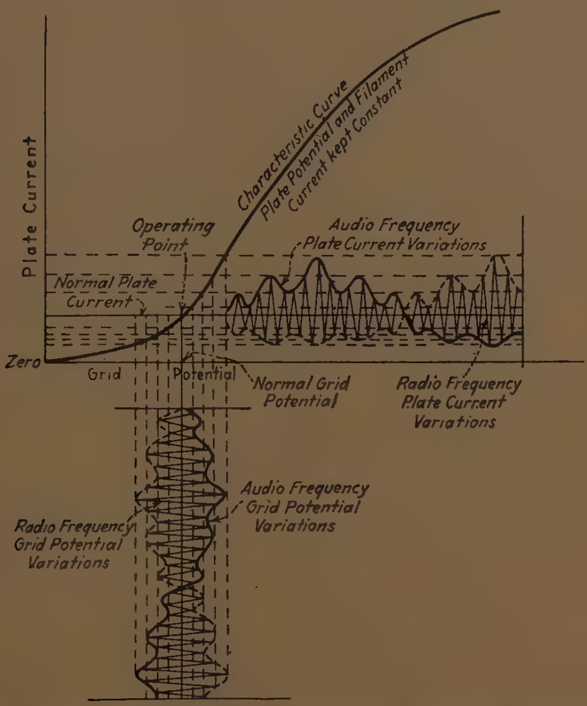


FIG. 89.—Detection of continuous oscillations as modified by the voice.

In this method, operation at the upper bend of the curve is very similar to that at the lower bend. But it should be noted that, for operation at the upper bend, equal variations of the incoming oscillations produce unequal variations of the plate current, so that the plate current is decreased more than it is increased. In operation at the lower bend, the plate current is increased more than it is decreased.

In plate rectification, the result of the action of the tube may be considered equivalent to that of a stage of radio-frequency amplification and a detector. This is because the radio-frequency voltage that is applied to the input is amplified in the plate circuit and changed to audio frequency.

Action of a Vacuum Tube without Grid Leak and Resistance. It may be shown that the average value of the change in plate current for weak signals is

$$\frac{E^2}{4} \times \frac{d^2I_p}{dE_g{}^2}$$

where E is the maximum value of the radio signal voltage impressed on the grid, and $d^2I_p/dE_g{}^2$ is the rate of change of the slope of the curve for the variation of plate current with grid voltage.

The average value of the change in plate current increases most rapidly when the curve in Fig. 82 bends sharply at the "point of operation" or when the slope of this curve changes rapidly. Operation at the lower bend of this curve is preferable, because at the upper bend the grid is positive and the conductance of the input circuit is high enough to result in considerable damping of the receiving circuit.

Non-oscillating Vacuum Tube Used as Detector with Grid Leak and Condenser.—Louder radio signals are obtained with many tubes if the grid is made positive with respect to the negative end of the filament so that a current flows in the grid circuit. Under these conditions the tube, instead of operating on the bend of the curve showing the variations of plate current with grid voltage, operates on the bend of the curve showing how the grid current varies with the grid voltage and on the straight portion of the curve showing variations of plate current with grid voltage. In the operation of this method a fixed condenser C is connected in series with the detector tube and the circuit of Fig. 86, as shown in Fig. 90. It should be noted that the grid return wire is connected to the positive terminal of the "A" battery.

When an incoming radio signal as represented in Fig. 91 is received by this circuit, similar voltage variations are communicated to the grid through condenser C. Each time the

grid becomes positive, the grid current which flows at the voltage e_0 increases more than it decreases when the grid voltage becomes less than e_0. This means that when the grid voltage becomes positive with respect to the filament, electrons are attracted to the grid, and when the grid voltage becomes negative during the next half cycle, the electrons cannot get away from the grid because they are "*blocked*" by the condenser C. As this action continues, more electrons are "trapped" on the grid. Hence, the grid continues to gain negative charges and the mean value of grid voltage becomes more and more negative with increasing strength of the incoming oscillations as shown at (3) in Fig. 91. This negative grid charge opposes the flow of electrons to the plate and magnifies the decrease in plate current as shown at (4) in the same figure. This charge can leak off through the condenser C or through the walls of the vacuum tube. If the insulation of the circuit and the condenser were perfect, the plate current would be so reduced that the tube would "*block*." But in order to make certain that this leakage occurs at the proper rate, a resistance R of a few megohms called a *grid leak* is shunted across the condenser C. In a *soft tube* a grid leak is not needed because the charge can leak from the grid to the filament by means of the conducting path through the gas with which the tube is filled.

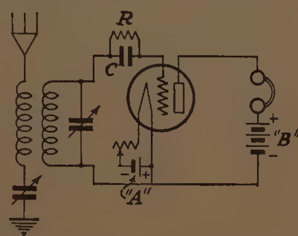


FIG. 90.—Non-oscillating tube used as detector with grid leak and condenser.

Values of the capacity C range from 150 to 500 micromicrofarads and the grid-leak resistance varies from 1 to 8 megohms. The value of R is such that the rate of leakage is proportional to the *period* of the *audio-frequency* variations of the radio-frequency oscillations and not to the *period* of the *radio-frequency oscillations*. The form of the current which flows through a telephone receiver is represented at (5) in Fig. 91.

In this method of detection (grid rectification), the operation is carried out on that portion of the curve showing variations

of grid current with grid voltage which has the greatest curvature. At the same time, the plate voltage is so adjusted that the operation of the tube takes place on the steepest portion of the curve showing plate current variations with those of grid voltage. In order to meet these conditions, the grid must be positive with respect to the negative end of the filament. The

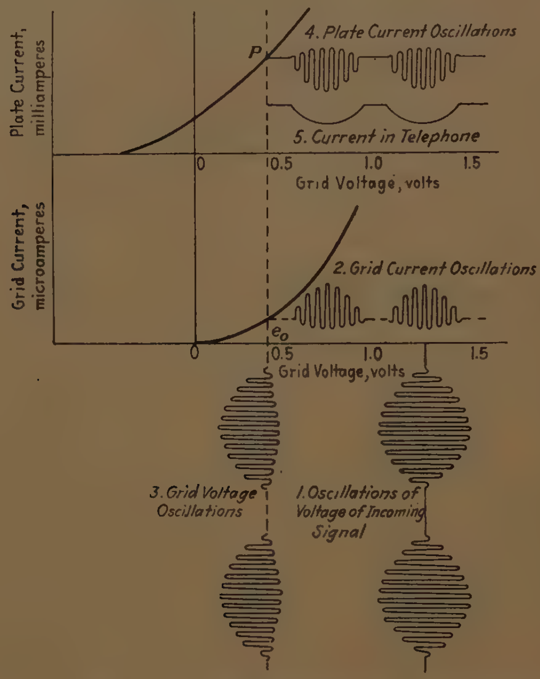


FIG. 91.—Use of detector tube with grid condenser on modulated continuous oscillations.

average voltage difference between them may be found, approximately, at the point of greatest curvature of the curve of grid current.

When a radio signal is received, the voltage of the grid depends upon the value of the grid leak resistance, the shape of the curve of the relation of grid current to grid voltage, and the relative voltage of the point to which the grid return is con-

nected. If the capacity of the grid condenser is too small, it will not allow the radio-frequency voltage to be impressed on the grid without acting through the resistance and, thus, decreasing the voltage. The reactance of the condenser should be less than the grid-filament impedance. If the condenser has a too high capacity, it requires more charge and thus may retard changes of grid voltage. This would impair the detecting action of the tube which depends upon the fluctuation in average grid voltage.

In grid rectification, the result of the action of the tube may be considered equivalent to that of a detector and a stage of audio-frequency amplification. This is because the radio-frequency voltage applied to the input is changed to audio frequency in the grid circuit and the audio-frequency variations are amplified into the plate circuit.

Action of a Vacuum Tube with Grid Condenser.—The average value of the change in plate current for weak signals is

$$\frac{E^2}{4} \times \frac{dI_p}{dE_g} \times \frac{d^2I_g}{dE_g^2} \div \frac{dI_g}{dE_g}$$

where E is the maximum value of the radio signal voltage impressed on the grid diminished by the voltage drop across the grid condenser, d^2I_g/dE_g^2 is the rate of change of the slope of the curve showing values of grid current corresponding to values of grid voltage, dI_g/dE_g is the slope of the same curve, and dI_p/dE_g is the slope of the curve showing how the plate current varies with changes in grid voltage.

In the action of a detector tube used with a grid condenser the effect of grid rectification, which tends to cause a decrease in the average plate current, is stronger than the effect of plate rectification which tends to cause an increase. Detection, therefore, with a grid condenser causes a decrease in the average value of the plate current.

Coefficient of Current Detection.—The varying plate current of a vacuum tube may be considered to consist of one current proportional to the alternating grid voltage, and another proportional to the square of that voltage. It is this latter current which produces the effect of detection.

The coefficient of this second term in the expression for plate current can be taken as a measure of the detection current, that is, the audio-frequency component of the output. The current detection coefficient is obtained from the second derivative of the curve showing the relation between plate current and plate voltage. For the case in which the plate circuit contains only a resistance, Van der Bijl gives the *current detection coefficient a*, in terms of the structural constants of the tube as

$$a = -\frac{u^2 r_p r_p'}{2(r_p + r_0)^3}$$

where

u = amplification factor.
r_p = plate resistance, ohms.
r_0 = external output resistance, ohms.
r'_p = variation in plate resistance due to curvature, ohms (derivative of conductance).

Effect of Operating Voltages on Detection Current.—In detection *without* a grid leak and a condenser if the detection

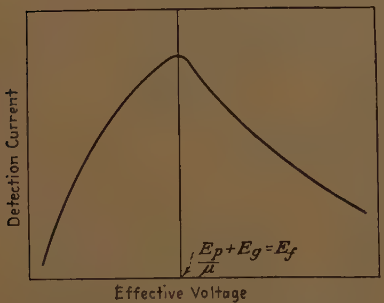


FIG. 92.—Effect of operating voltage on detection curve without grid leak and condenser.

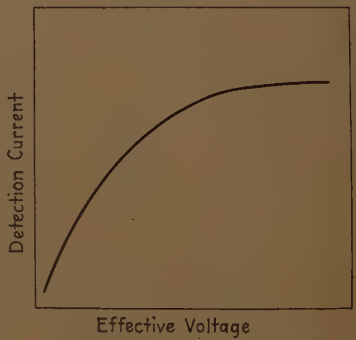


FIG. 93.—Effect of operating voltage on detection curve with grid leak and condenser.

current is measured in terms of the effective voltage $E_p + E_g$, the relation is shown as in Fig. 92. The maximum value occurs when the effective voltage is equal to the voltage drop in the filament, E_f. In detection *with* a grid leak and con-

denser if the detection current is measured in terms of the effective voltage $\frac{E_p}{u} + E_g$, the relation is shown as in Fig. 93.

Efficiency of Vacuum Tube as a Detector.—The intensity of sounds from telephone receivers in the plate circuit of a detector tube in which the detecting action depends upon the bend of the characteristic curve varies as the square of the current flowing through the telephone receivers. The changes in plate current vary as the square of the voltage impressed on the grid for weak radio-signals. The sound intensity, therefore, varies as the fourth power of the grid voltage. Further, the voltage on the detector tube is proportional to the voltage or current in the antenna circuit so the above relations can be given in terms of these quantities. It is evident that all vacuum tubes are inefficient as detectors of weak radio signals. If the antenna current is reduced to one-half, the received power is reduced to one-quarter, the plate current is reduced to one-quarter, the output power is reduced to one-sixteenth, and the efficiency to one-quarter. For tubes in use at the present time, the received voltage impressed on the grid of the detector tube must be of the order of several hundredths of a volt to get satisfactory reception.

Although the detection coefficient a gives an indication of the detecting current, it is affected by the impedance of the load on the tube and consequently is not the best quantity to use for measuring the detecting efficiency of a vacuum tube. A better way of expressing the detecting efficiency is to consider it as the ratio of audio-frequency output power to radio-frequency input power. The former is the product of the square of the detecting current and the external resistance in the output circuit of the detector. The radio-frequency input power is not easily measured because it is affected by the constants of the output circuit. But there is a definite relation between the audio-frequency power output and the radio-frequency *voltage* input so it is better to express the detecting efficiency of a vacuum tube in terms of these quantities. The detecting efficiency then is given as a^2r_0, where a is the detection coefficient and r_0 is the external output resistance in ohms.

Effect of Strong Signals.—The effect of a strong radio signal is to increase the efficiency of the detector tube. Under such a condition, the response is proportional to the first power of the impressed grid voltage; that is, the audibility varies directly as the received voltage or current in the antenna.

Comparison of Detection by Grid Rectification and by Plate Rectification.—The grid rectification method of detection is more sensitive than plate rectification and to this extent is better when the input voltages are small. Overloading, however, will occur more readily with the former. When the input voltage is large, plate rectification may be used to take full advantage of the greater output available and of the freedom from distortion which results from overloading. In this circuit arrangement, the impedance of the tube is rather high so that the primary of the first audio-frequency transformer should have a high inductance.

It would seem, then, that more sensitiveness is obtained with grid-leak detection, but that best quality of reproduction results from "C" battery or grid-bias detection. In a regenerative detector, however, one method may be just as sensitive as the other. Furthermore, some authorities claim that for tubes such as UX-201A, UX-199, and UX-112A, grid-bias detection is superior to grid-leak detection with respect to quality and selectivity and need not be less effective with regard to sensitivity.

A recent study[1] of detection for weak radio signals brings out a number of interesting conclusions. A rectifying detector depends in its action upon a non-linear relation between the instantaneous output current and the instantaneous applied voltage. If the impressed modulated voltage of a radio signal is small, the output contains the following components: (1) a constant current; (2) a current of modulation frequency; (3) a current of double modulation frequency; (4) and currents of frequencies equal to the sum and difference of the several modulation frequencies. All of these component currents are proportional to the square of the impressed

[1] Chaffee and Browning, "A Theoretical and Experimental Investigation of Detection for Small Signals," *Proc. I. R. E.*, Feb., 1927.

voltage of the radio signal. The component of modulation frequency is proportional to the degree of modulation; all others depend upon the square of the modulation or upon the product of the two modulation factors, and, hence, are small in comparison with the current of modulation frequency, if the degree of modulation is small.

The voltage detection coefficient[1] is a better measure of the detecting action of a rectifying detector tube because its value is independent of the impedance interposed in the plate circuit during the measurement of the detection coefficient. The voltage detection coefficient gives an equivalent voltage which, considered as acting in the plate circuit, gives the audio current which flows through the circuit containing r_p and the plate impedance normally used with the detector. A knowledge of r_p is thus necessary.

A *hard tube used without* a grid-circuit impedance, that is, a "blocking" condenser and grid leak or the equivalent, and with no radio-frequency impedance in the plate circuit, depends for its detecting action entirely upon the bends of the plate-current curve. The resulting detection is usually very small. A gas (soft) tube when used in this way gives much greater detection than a similar tube highly exhausted because ionization increases both the upper and lower bends of the plate-current curve. Ionization also causes kinks in the plate-current curve resulting in a high sensitivity at such points because of the very large values of the ratio of small changes in grid-plate conductance to small changes in grid voltage. A radio-frequency impedance in the plate circuit of a hard tube used without a grid impedance decreases the detection coefficient due to the lower bend of the plate-current curve. A tickler usually more than makes up for this decrease in detection coefficient by increasing the strength of the impressed radio signal. All audio-output devices in the plate

[1] The term *current detection coefficient* has already been explained. The expression for current detection coefficient multiplied by the total resistance of the circuit, for a small change in current, gives an expression called the *voltage detection coefficient*. This is a name for the equivalent steady voltage produced by rectification acting in the output circuit.

circuit should be shunted by a condenser having a small reactance for radio-frequency currents.

The sensitivity of a hard tube used *with* a grid impedance depends upon the product of grid-plate conductance and the ratio of small changes in grid conductance to small changes in grid voltage and, also, upon a factor F which is equal to the equivalent parallel impedance of the grid impedance and the grid-to-filament resistance. For this case, when a hard tube is used, the sensitivity is usually much greater than the maximum sensitivity obtainable without a grid impedance. The grid-plate conductance should be made large by using the proper plate voltage. The value of the product mentioned above is a maximum for biasing voltages of a few tenths of a volt, when positive, but F falls so rapidly for positive grid voltages, due to the increase of grid conductance, that the point of maximum sensitivity is found at a grid voltage more negative than that which gives a maximum value of the product. The detection-coefficient curves have very narrow peaks so that it is necessary to adjust the grid-biasing voltage to the proper value, usually 0.1 or 0.2 volt positive. Because of the steady rectified component of current in the grid circuit, a strong radio signal unfortunately alters the biasing voltage.

The ordinary grid leak and "blocking" condenser is not the best form of grid impedance because of its variation with the frequency, and especially its large value at zero frequency. The ideal impedance is one having negligible resistance to steady currents, a high impedance for frequencies from 100 to 10,000, and low impedance for the radio-frequency current.

A tickler coil used with a detector provided with a grid impedance increases the detection coefficient.

Experiments show that a tube having a high-amplification factor is usually more sensitive as a detector than one having a low-amplification factor.

Effort of Static on Detection.—A strong impulse due to a static pulsation may cause a variation in the plate current a hundred or even a thousand times as great as that caused by the radio signal in a tube having the usual characteristic shown in Fig. 94.

A tube having a low emission and operating at low plate voltages would impose a severe limitation on the effect of static. Thus, consider the characteristic curve of the tube shown in Fig. 95 in which the operating plate current and the plate voltage are, respectively, about 1/10 and 1/4 of those of the tube in Fig. 94. Both the maximum and the operating currents are low in value. A variation of the grid voltage, therefore, in either direction cannot cause a disturbance of the same magnitude as that mentioned above.

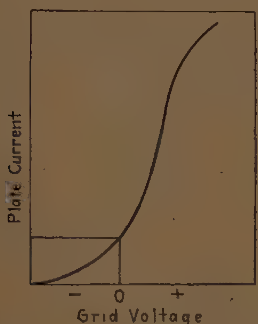


Fig. 94.—Characteristic curve of typical vacuum tube showing low and high bends.

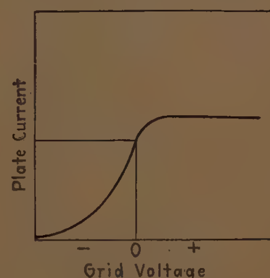


Fig. 95.—Characteristic curve where operating plate current and plate voltage are much less than in Fig. 94.

Detection with Alkali Vapor Vacuum Tube.—The alkali vapor tube UX-200A which is filled with caesium vapor is intended for use as a detector. The filament is the same as that used in a UX-201A but a finer grid mesh is provided to produce a higher amplification factor, which contributes to greater sensitivity as a detector. The filament must carry enough current to make the tube fairly warm. Stable action does not begin until, after a few minutes of operation, the warming up is completed. As the tube begins to get warm, the plate current increases slowly at first and then more rapidly. Then, finally, it ceases to rise and decreases to a steady value when the tube reaches its final temperature.

When the tube is first lighted, a hiss is produced which continues for a few minutes. While the plate current is increas-

ing, the hissing sound increases to a maximum, then decreases and disappears when the plate current is steady. The occurrence of this hiss with relation to plate current variation is clearly shown in Fig. 96 for a tube using a potassium-sodium alloy as the vapor pressure increases.

The amount of noise produced by the UX-200A tube diminishes as a broadcasting station is tuned in. This behavior may be demonstrated by operating the volume control at a time when a station, tuned in, is "on the air" but is not broadcasting. Any noise which may be present decreases rapidly as the volume control is turned from soft to loud volume.

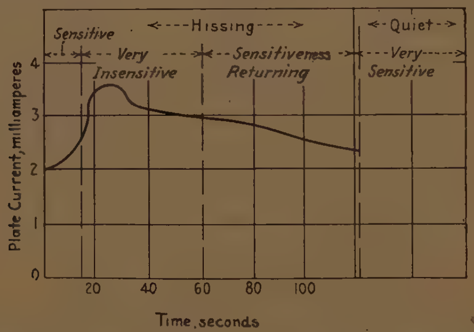


FIG. 96.—Relation of hissing sounds to intensity of plate current in alkali vapor tube.

This shows that the noise does disappear and is not "drowned out" by the broadcasting. A tube which does not become quiet when tested in this manner should be checked for leakage.

Detection with a UX-200A tube may be accomplished by either grid-current rectification or plate current rectification. The usual sizes of grid condenser and grid leak are satisfactory, that is, 0.00025 microfarad and 2 megohms, respectively. The preferred connection for the grid return is to the negative filament. When a grid leak and condenser are used, the tube automatically reaches the correct point of operation because the flow of grid current through the grid leak builds up the required negative voltage. This is the only function performed by the grid leak in the case of this tube. Best detection is obtained by operating the tube at the point where the

curvature of the curve showing variations of grid current with grid voltage is greatest. This occurs at a grid voltage of slightly more than −2.0 volts as shown in Fig. 97 for a plate voltage of 45 volts.

The curves which show the variations of plate current with plate voltage for the UX-200A tube are drawn in Fig. 98 for three values of grid-bias voltage; 0, −1.5, and −3.0 volts. The curves in this figure differ from similar curves for other tubes because a moderately high plate current flows when both the plate and the grid voltages are zero. The plate

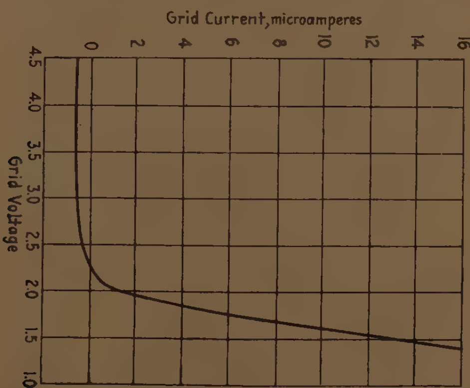


FIG. 97.—Characteristic curve showing best point of operation of UX-200A tube.

current, in this case, is not reduced to zero until a negative grid bias of about 3 volts is applied. This flow of plate current is due to the presence of positively charged ions of gas in the space between the electrodes. A plate voltage of 45 volts is recommended but any voltage above 22½ volts may be used. The best quality of reproduction and the maximum sensitivity are obtained at 45 volts because the plate impedance is rather high at low plate voltages. Above 45 volts the detector action decreases rapidly and there is consequent noise.

The UX-200A tube is more sensitive than the UX-200 tube when the latter is critically adjusted and it attains this sensitivity without a critical adjustment of either the filament or the plate voltage. No marked increase in signal strength is

noticed when the UX-200A tube is used in a radio receiver which is "tuned in" at full volume on a local broadcasting station as compared with type UX-200 or UX-201A. A marked improvement in signal intensity and clarity of reproduction is obtained, however, on distance reception, because of the greater response given by the UX-200A tube on weak radio signals. The selectivity of a receiver using a UX-200A tube is

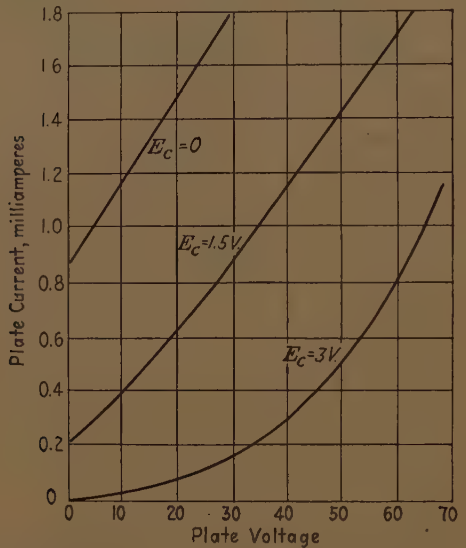


FIG. 98.—Characteristic curves for three values of grid bias voltage.

decreased somewhat but may be improved by a shorter antenna or by coupling the antenna more loosely to the receiver. The performance of the UX-200A tube, when used with transformers which have a resonant peak at high frequencies due to the distributed capacity of the windings, may be improved by eliminating the peak by the method of inserting a 5-megohm grid leak across the secondary of the transformer.

The UX-200A tube delivers an audio-frequency voltage output which is several times as great as that of the UX-201A. This is illustrated in Fig. 99 which shows the relation between

audio-frequency output in millivolts and radio-frequency input. Under the conditions of this test, the radio signal is completely modulated, the output is measured across the primary of the transformer, the grid leak has a resistance of 3 megohms, and the grid condenser a capacity of 0.00025 microfarad.

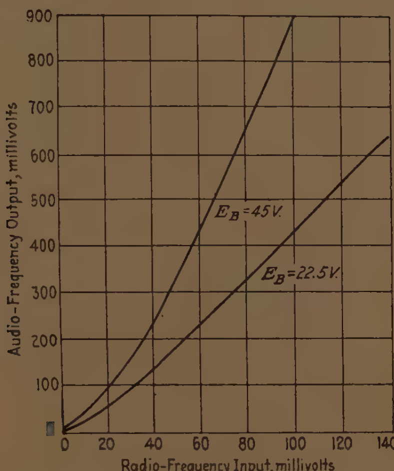


FIG. 99.—Audio-frequency output curves of detector tube with output measured across primary of transformer for two values of "B" battery voltage.

The audio-frequency voltage in the output circuit is quite critical with respect to the adjustment of the grid bias. Figure 100 shows the performance of a UX-200A tube when the audio-frequency output voltage is plotted as a function of the grid-bias voltage with a plate voltage of 45 volts. This curve indicates the necessity for potentiometer adjustment when a grid bias is used instead of a grid condenser and grid leak. A grid bias of -1.5 volts or less causes a decrease in sensitivity and an increase in damping of the input circuit due to a larger grid current.

It is generally assumed that tube detectors obey a "square-law" relation; that is, that the change in plate current dI_p is equal to $K(E_g)^2$ where E_g is the radio signal voltage impressed

on the grid. For alkali vapor detector tubes $dI_p = K(E_g)^X$ where X is nearly unity. This approximates more closely the desired condition of ideal linear rectification.

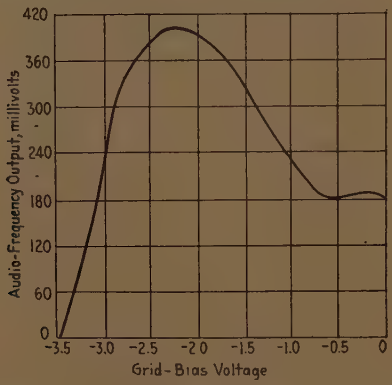


FIG. 100.—Variation of audio-frequency output with changes of grid-bias voltage for UX-200A tube.

Detection with Tubes having Filaments for Alternating Current.—Vacuum tubes in which the filament is heated by alternating current operate under such conditions that it is necessary to reduce to a minimum the voltage ripple due to this kind of current.

The UY-227 tube which is intended for use as a detector with alternating current supplied for heating has an oxide-coated metallic cylinder instead of the usual filament. This cylinder is heated by an internal tungsten filament which is insulated from the cylinder. The fluctuations in temperature which occur at the rate of 120 cycles per second when the internal filament is heated with alternating current are prevented from affecting the performance, of the tube because of the thermal inertia of the cylinder and the insulating material. The surface temperature variations of the emitting cylinder, therefore, are so slight that no appreciable ripple voltage is produced. The grid and plate of the UY-227 are of the cylindrical form similar to that used in UX-199 tubes.

The UY-227 tube may be used with either grid-circuit or plate-circuit rectification. The method of detection has little effect

on the amount of ripple voltage. A ripple voltage of a few millivolts followed by normal audio amplification is not audible at even a short distance away from the loud speaker. The ripple voltage is kept at a minimum by connecting the center tap of the detector filament transformer winding, which is in the circuit of the filament of the detector tube, to the positive detector tap, putting 22½ to 45 volts between the "heater" filament and the "emitting" cylinder. A potentiometer return may be used instead of the transformer tap but the slight effect on ripple voltage of changes in the potentiometer setting usually makes this construction unnecessary.

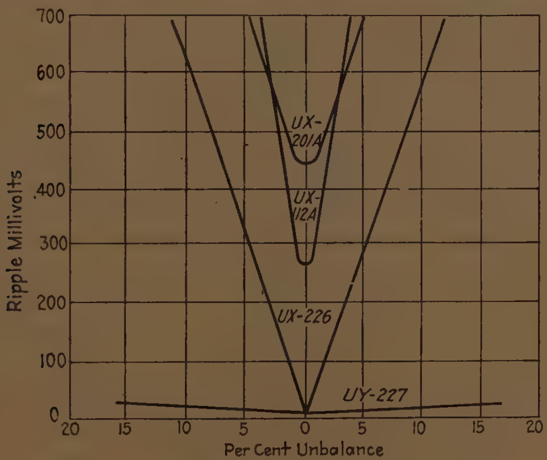


FIG. 101.—Ripple voltage of several standard tubes.

The UX-226 tube which is intended for use as an amplifier has characteristics similar to the UX-201A tube, and is provided with a low-voltage, heavy-current, oxide-coated filament in the form of an inverted *V*. The filament current and voltage ratings are selected to obtain a close balance between the electro-magnetic and electro-static fields due to the alternating current, and this balance is made to occur at the point of most satisfactory operation as an amplifier.

The difference between the amplifying UX-226 tube and the detecting UY-227 tube, when compared as detectors, is readily seen from the ripple voltage produced by each of the tubes as

the degree of unbalance from the exact neutral point of the supply system is varied. A comparison of four types of tubes is shown in Fig. 101. These curves show the lower minimum value of ripple voltage of the UX-226 tube as compared with the UX-112A and the UX-201A tubes and they also show that the grid return is less critical. The grid return of the UY-227 tube is not at all critical as might be expected from the type of construction. The grid return of a tube operated with alternating current must be connected to the exact neutral point, because any other connection impresses a 60-cycle voltage on the grid and consequently produces a rapid increase in the ripple voltage.

Detection with Four-element Tubes.—When a UX-222 tube is used as a detector, it gives an audio-frequency amplification of 40 to 75 per stage. The utilization of such high audio-frequency amplification is troublesome because of the increased difficulty from frequency distortion which is due to the coupling between the tubes which are in a common battery or power supply circuit, and also because microphonic disturbances in the detector cause more disturbance.

The amplification of a UX-222 tube can be utilized by using the tube as a detector and eliminating the first stage of audio-frequency amplification. Under these conditions the detector tube must be able to take a radio-frequency input voltage of several volts and must be able to supply 20 to 30 volts to the grid of the power tube.

The high radio-frequency amplification, which is necessary to give to the detector tube a radio signal of several volts, may be obtained by using a *screen-grid tube*[1] as a radio-frequency amplifier.

The method of grid-leak detection is not possible because it cannot operate on a heavy radio-frequency input voltage without overloading. It reduces also the selectivity of the tuned circuit because of damping. Plate rectification with the UX-222 tube does not have these limitations.

[1] A *screen-grid vacuum tube* is constructed so that there is a fourth element called a "screen grid" which is used as a shield around the plate and serves to "screen" the control grid from the effect of the plate.

In the theoretical screen-grid tube[1] the only factor affecting the output of a vacuum tube under usual operating conditions is the *mutual conductance*, because the plate current is independent of the plate voltage, and because there is but little capacity between the control grid and the plate. Voltage amplification is equal to the product of the mutual conductance and the external impedance. The amplification factor varies with the plate, control-grid, and screen-grid voltages, but has

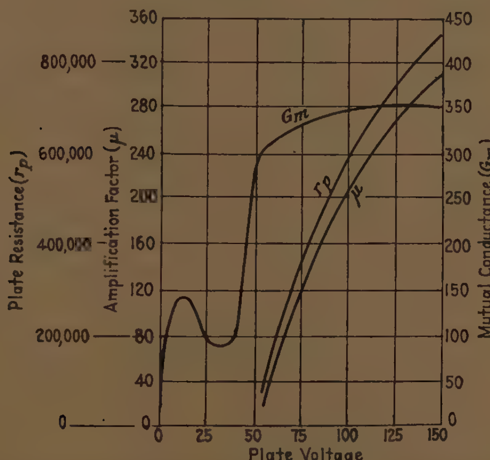


FIG. 102.—Relation of constants of screen-grid tube at various plate voltages.

a definite value as soon as all the voltages are specified. The relations between the various constants of this tube such as r_p, G_m, and u, and the plate voltage are shown in Fig. 102

when

$$E_{c1} = 1.5 \text{ volts}$$

and

$$E_{c2} = +45 \text{ volts.}$$

The relations between these constants and the control-grid voltage are shown in Fig. 103

[1] A complete description and theory of the screen-grid tube is given in "Characteristics of Shielded Grid Pliotrons," by HULL and WILLIAMS, *Physical Review*, April, 1926.

when

$$E_{c2} = +45 \text{ volts.}$$

A consideration of Fig. 104 which indicates the elements of a circuit using the UX-222 tube shows a number of interesting conditions. This circuit has no input impedance because

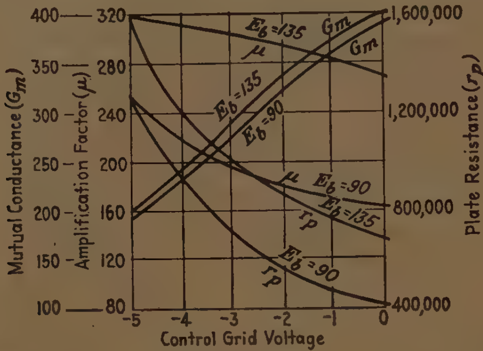


FIG. 103.—Relation of constants of screen-grid tube at various grid voltages.

there is no mutual capacity between the control grid and the plate. The interelectrode capacity of the control grid to the filament is considered a part of the tuning capacity C. There can be no grid rectification in this case because there is no low-frequency grid impedance. There is no control-grid current because of the negative bias on the control grid. Thus, the internal impedance from control grid to filament is extremely large. A fixed positive bias from a direct-current source is applied to the screen grid. The effect of this screen grid, however, is constant. Since there is no impedance in the screen-grid circuit, it has a zero potential for alternating current. The plate current, then, is a function of only two variables, the voltage on the plate and that on the control grid.

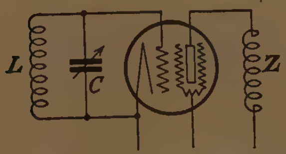


FIG. 104.—Circuit using UX-222 tube.

The steady value of the plate current I_p is given in this case in amperes by the following relation:

$$\frac{r_p}{r_p + R} \times \frac{dG_m}{dE_g}\left(1 + \frac{B^2}{2}\right)\frac{A^2}{4}$$

In this equation which applies to the use of the tube as in Fig. 104, r_p is the plate resistance of the tube, R is the direct-current resistance of Z, dG_m/dE_g is the first derivative of mutual conductance G_m with respect to the voltage of the control grid E_g, B is the degree of modulation expressed as a decimal and A is the peak value of the radio-frequency voltage impressed on the grid. The relation between plate current and plate voltage varies according to the "square law" because dG_m/dE_g decreases with input voltage, and because r_p decreases as the input voltage decreases.

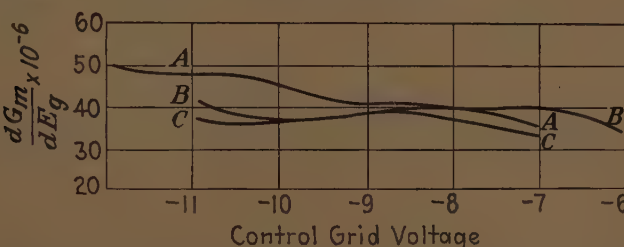


FIG. 105.—Relation of first derivative of mutual conductance with respect to control of grid voltage as the control grid voltage varies for three conditions of plate and screen-grid voltages.

The curves of Figs. 105 and 106 give the relation between dG_m/dE_g and control-grid voltages with respect to plate voltage and screen-grid voltage under different conditions of operation. In Fig. 105 the conditions for the curves A, B, and C are as follows:

A—static value, $E_p = 135$ volts, $E_{c2} = 67\frac{1}{2}$ volts,
B—dynamic value, $E_p = 225$ volts, $E_{c2} = 67\frac{1}{2}$ volts,
C—dynamic value, $E_p = 135$ volts, $E_{c2} = 67\frac{1}{2}$ volts,

where E_p is the plate voltage and E_{c2} is the screen-grid voltage.

In Fig. 106 the conditions for the curves A and B are as follows:

A—static value, $E_p = 135$ volts, $E_{c2} = 45$ volts.
B—dynamic value, $E_p = 135$ volts, $E_{c2} = 45$ volts.

It is obvious that although the value of dG_m/dE_g, is practically constant, it decreases as the control-grid voltage is made less

negative. Another relation is shown in Fig. 107 where the value of dG_m/dE_g is approximately constant for input voltages

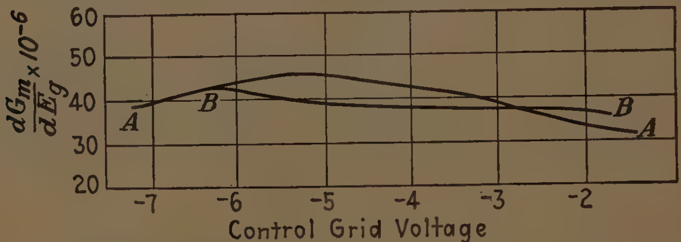


FIG. 106.—Relation of first derivative of mutual conductance with respect to control grid voltage as the control grid voltage varies for two conditions of plate and screen-grid voltages.

nearly as great as the control-grid bias but decreases somewhat as the input voltage is increased. For these curves the grid bias voltage, E_{c1} was -7.5 volts and E_{c2} was $+45$ volts.

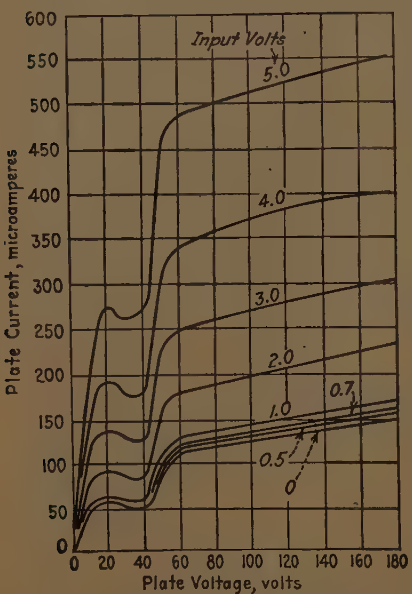


FIG. 107.—Curve showing variation of plate current with plate voltage for various input voltages.

If R is constant, the value of $\frac{r_p}{r_p + R}$ decreases with an increase of r_p. The variation of plate resistance with plate current when the plate voltage and screen-grid voltage are constant is illustrated in Fig. 108. If $R = 400{,}000$ ohms and r_p varies from 4 megohms to 1 megohm, the value of the term $\frac{r_p}{r_p + R}$ changes from 0.91 to 0.71.

The drawing in Fig. 109 shows the variation of the current with the plate voltage of a UX-222 tube for various plate input voltages at 1,000 kilocycles. Different load lines are

drawn from the point corresponding to 270 volts. The voltage applied to the screen-grid was $E_{c2} = +67.5$, and the grid-bias voltage was $E_{c1} = -12.3$ volts. This tube was used as a

FIG. 108.—Variation of plate resistance with plate current when plate and screen-grid voltages are constant.

detector in the circuit of Fig. 110. Here, $R = 5 \times 10^5$ ohms, $r = 2 \times 10^6$ ohms, and $C = 0.2 \times 10^{-6}$ farads. The alternating-current impedance of the combination is approximately 4×10^5 ohms.

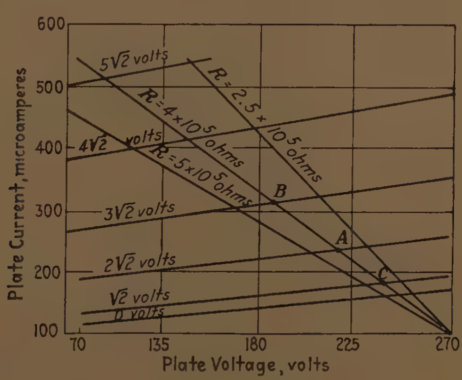


FIG. 109.—Variation of plate current with plate voltage of UX-222 tube for various input voltages and loads.

The output voltage for a given input voltage and load may be obtained from the curves that have just been mentioned. Thus, with a load of 400,000 ohms, an input voltage of 2 volts

(root mean square value), modulated 50 per cent, the point A is taken as a reference. The alternating voltage across the resistance R will vary in value between B and C. This corresponds to an output voltage variation of approximately 52 volts, so that the peak value is one-half of the total or 26 volts. For 40 per cent modulation, the peak value would be 80 per cent of this or 20.8 volts. For any given input voltage it is only necessary to draw two other curves; that is, for example, with an input of $2\sqrt{2}$ volts curves may be drawn for values of input of $\sqrt{2}$ and $3\sqrt{2}$ volts. Then, the variation of voltage at 50 per

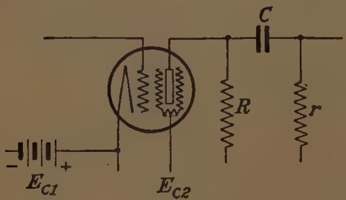


FIG. 110.—Typical circuit using UX-222 tube as detector.

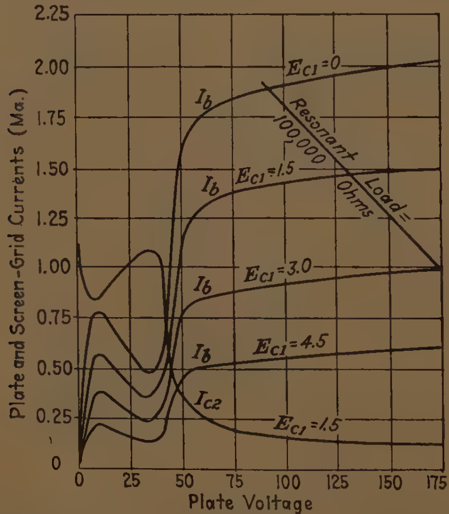


FIG. 111.—Variation of plate and screen-grid currents with plate voltage for various values of grid-bias voltage and constant value of screen-grid voltage (+45 volts).

cent at modulation is found, and, since the output voltage is proportional to modulation, its value for other degrees of modulation may be found. Two other forms of curves

showing how the plate current varies with the plate voltage are given in Figs. 111 and 112. The data shown in Fig. 111 were obtained with a value of +45 volts for E_{c2}, while those in Fig. 112 were obtained with $E_{c2} = +22\frac{1}{2}$ volts.

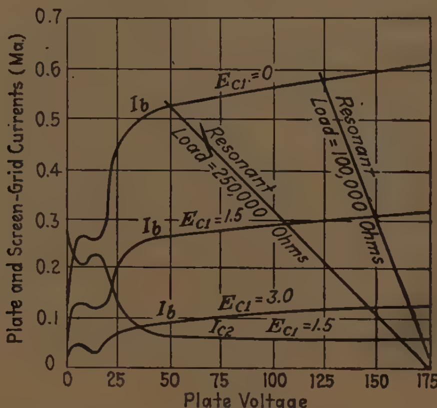


FIG. 112.—Variation of plate and screen-grid currents with plate voltage for various values of grid-bias voltage and constant value of screen-grid voltage (+22½ volts).

Non-oscillating Tube as Detector with Regeneration.—It has been shown that the radio-frequency portion of the plate current of a detector tube does not enter into any action on the telephone receiver or other apparatus in the plate circuit. This radio-frequency current may be used to increase the radio-frequency voltage in the input circuit. To accomplish this a feed-back coil is coupled to the secondary coil in the grid circuit. For a given radio signal strength, the radio-frequency voltages and currents are increased by the effect of regeneration and, consequently, the volume of sound is also increased. This action is cumulative up to a certain point, but beyond this value the tube begins to oscillate. A more complete description of regeneration is given in Chap. IX, but this elementary description serves to introduce the conception of an oscillating tube.

Oscillating Tube in Reception.—The frequency of an incoming radio-frequency current may be changed by another

method which depends upon the interaction of two currents of slightly different frequencies. Thus, if the input circuit is forced to carry a locally generated current having a frequency either greater or less than that of the incoming current, there is an interaction between the two frequencies which produces a current of a third frequency equal to the numerical difference between the other two. This general method is called *heterodyne action* and the current of the third (and lower) frequency is called the *beat current*. When the same tube generates the local oscillations and acts also as a detector, the action is known as *autodyne* or sometimes as *self-heterodyne*. When an additional tube is used to generate the local oscillations, the action is called *separate heterodyne*. The so-called *superheterodyne* or *multiple-heterodyne* method of reception is based on the use of several separate heterodyning and detecting stages. These various methods will be considered briefly in Chap. VIII.

CHAPTER VIII

USE OF VACUUM TUBES AS AMPLIFIERS

The action of a vacuum tube in amplification may be determined by obtaining the relations between the instantaneous currents and voltages in both its input and output circuits. The current in one of these circuits depends upon the voltages in both. Further, the relations between currents and voltages in a vacuum tube which were considered in a study of "static" characteristics in Chap. VI were taken with steady applied voltages and no external load. In order to get a clear understanding of the effect of these conditions upon amplification, it is necessary to examine the action of the vacuum tube with respect to the input and output circuits.

Input Circuit.—The resistance r_g of the input circuit (grid-filament circuit) to direct current when the grid is negative, is practically infinite. When, however, the grid is positive, the grid current varies as the square of the grid voltage. If the value of the positive voltage on the grid is the same as that on the plate, the grid and plate currents are approximately equal.

The resistance r_g of the input circuit increases as the voltage E_p is increased; in other words, the conductance G_g decreases. The conductance increases with increasing filament current, and decreases as the grid-bias voltage is made more negative. The latter relation is the basis of one method for the control of regeneration in tuned radio-frequency amplifiers. The conductance increases with increasing amplitude of input signal voltage. Thus, it is obvious that the grid must be negative with respect to the filament if the input resistance of the vacuum tube is to be kept high.

The effect of the interelectrode capacity on the circuit capacity has already been mentioned (page 75). It may be

shown that the capacity of the input circuit varies with the voltage amplification factor of the tube and with the kind of circuit. The mutual capacity of the internal grid-filament capacity of the tube and the internal grid-plate capacity of the tube may produce a voltage in the former which is in phase with the impressed grid voltage. The effect of this is to make the conductance of the input circuit negative and to allow the plate circuit to react on the input circuit so as to augment the impressed grid voltage. The capacity of the input circuit increases as the plate circuit resistance is increased, or as the plate circuit reactance is increased. Changes in frequency affect the plate reactance. Since the phase relations between the input voltage and the plate voltage depend upon the plate reactance, it is obvious that the input circuit characteristics will, also, be affected by frequency because they depend upon the voltage phase relations. Thus, the input capacity is decreased and the input conductance is increased by an increase in input frequency with resistance in the plate circuit. When the plate circuit is reactive, a change in input frequency either increases or decreases the characteristics of the input circuit of the tube depending upon the value of the reactance.

The effect of the input capacity has been described on page 73. It may be reduced by using some form of neutralizing circuit or a screen-grid vacuum tube.[1]

Impedance of the Input Circuit.—When a *steady* voltage is impressed on the grid circuit of a vacuum tube no grid current flows if the grid is negative with respect to the filament. But, when an alternating voltage is thus impressed an alternating current will flow in the grid circuit because of the path offered by the internal grid-filament capacity of the tube, and there will be, also, an alternating current in the plate circuit because of the internal grid-plate capacity of the tube. This action will take place whether or not the filament is emitting electrons. The power thus supplied is dissipated as heat in the resistance of the circuit. In order to maintain a high efficiency of amplification, it is necessary to reduce the former

[1] A screen-grid vacuum tube is described on p. 226.

as much as possible. In multi-stage amplifiers the phase difference between these alternating currents from the input source and the input voltage becomes an important factor.

The magnitude of the current due to the internal grid-plate capacity of the tube depends upon the alternating portions of the grid and plate voltages and upon the internal grid-plate capacity of the tube. It is equal to the voltage difference between grid and plate divided by the reactance of the grid-plate capacity, thus,

$$I_{g-p} = \frac{E_g - E_p}{\frac{1}{2\pi f C_{g-p}}} = 2\pi f C_{g-p} \times (E_g - E_p).$$

As shown later

$$E_p = uE_g\left(\frac{R_0}{r_p + R_0}\right).$$

Hence by substitution

$$I_{g-p} = 2\pi f C_{g-p} E_g\left(1 - \frac{R_0}{r_p + R_0}\right).$$

Likewise, the magnitude of the current due to the grid-filament capacity is

$$I_{g-f} = 2\pi f C_{g-f} E_g.$$

In these expressions

E_g = alternating portion of grid voltage, volts.
E_p = alternating portion of plate voltage, volts.
f = frequency in cycles per second.
R_0 = external resistance in plate circuit, ohms.
r_p = plate resistance of tube, ohms.
C_{g-p} = internal grid-plate capacity of tube, farads.
C_{g-f} = internal grid-filament capacity of tube, farads.
π = 3.1416.
u = amplification factor.

It is readily seen that the input impedance depends upon two circuits in parallel, one of which contains the reactance of the grid-filament capacity, and the other, the impedance of the grid-plate capacity in series with the external impedance in the plate circuit.

Effect of Load on Plate Current.—The output circuit of a vacuum tube contains the apparatus for using the detected and amplified variations of current and voltage. The voltage acting on the plate of a vacuum tube which has no load in the plate circuit is equal to the plate-battery voltage. But a tube in actual use as an amplifier may have one or more of the following in the plate circuit: a resistance, a primary of a transformer, an inductance, a loud speaker. When a varying plate current flows through such apparatus, the voltage acting on the plate is not constant because of the varying voltage drop across the load; that is,

$$E_p = E_b - I_pR_0$$

where

E_p = plate voltage, volts.
E_b = battery voltage, volts.
R_0 = external resistance, ohms.
I_p = plate current, amperes.

It has been shown that the effect of an alternating grid voltage E_g is to produce an alternating plate current uE_g/r_p, and that the effect of an alternating plate voltage E_p is to produce an alternating plate current E_p/r_p. The total plate current produced by grid and plate voltages in combination is, therefore,

$$I_p = \frac{uE_g}{r_p} + \frac{E_p}{r_p}.$$

This expression is true only if the plate current variations are small enough to extend only over the straight line portion of the plate current-grid voltage curve (page 62).

In the case of a resistance load R_0, the alternating current I_p flowing through R_0 produces an alternating voltage drop of $E_p = I_pR_0$. The effect of this voltage drop is opposite to the action of the grid voltage; that is, if the grid is made more positive, the plate current and also the voltage drop across R_0 increase, and consequently the plate voltage decreases. Or, if the grid is made more negative the plate current and, also, the voltage drop across R_0 decrease, and the plate voltage increases. Hence, when I_pR_0 is substituted for E_p it is given

a negative sign. When this substitution is made in the equation above, the plate current becomes

$$I_p = \frac{uE_g}{r_p} - \frac{R_0 I_p}{r_p}, \text{ from which } I_p = \frac{uE_g}{r_p + R_0}$$

that is, the alternating current I_p in the plate curcuit for an impressed grid voltage E_g is the same as that which would be caused to flow in a circuit having a resistance of $r_p + R_0$ by an alternating voltage uE_g.

It is advantageous to consider the action of a vacuum tube as similar to that of an electric generator. The steady values of plate and grid voltages and plate current are considered only in so far as they affect quantities such as the plate resistance. The grid is omitted from the discussion except when the matter of grid current must be taken into consideration. The tube may then be regarded in effect as a device in which there is connected between the plate and filament an alternating current generator having a resistance r_p and generating a voltage uE_g. The resistance r_p[1] is determined by the steady or non-varying grid and plate voltages. The alternating, or, more correctly, fluctuating plate current is produced by the voltage uE_g.

In a circuit containing only resistance, the impressed voltage is in phase with the current; that is, the variations of the impressed voltage occur in step with the variations of the current. The counter voltage is opposite in phase to the impressed voltage and to the resulting current. That is, in the tube circuit the plate current is in phase with the grid voltage, the phase difference between the plate voltage and plate current is 180 degrees, and the phase difference between the plate voltage and the grid voltage is 180 degrees.

Since the plate voltage E_p acting on the tube is equal to $E_B - I_B R_0$, where I_B is the battery current, it is evident that when an external resistance is inserted in the plate circuit additional "B" battery voltage must be supplied to maintain the plate voltage at its proper value. If this is not done, the plate voltage E_p decreases, r_p increases, and the voltage ampli-

[1] Actually, of course, r_p does vary with the alternating plate current.

fication is reduced. When $R_0 = r_p$ the battery voltage E_B must be about 50 per cent larger than the rated plate voltage of the tube. Under these conditions, a voltage amplification of $u/2$ is obtained.

Impedance Load.—The derivation of the expression for the value of plate current can readily be extended for the case of an impedance load. Thus consider that the plate circuit contains a loudspeaker having a resistance R_0 and an inductance L. The impedance Z of the plate circuit is $Z = \sqrt{(r_p + R_0)^2 + (2\pi fL)^2}$. The voltage divided by the impedance gives the current as $I_p = \dfrac{uE_g}{\sqrt{(r_p + R_0)^2 + (2\pi fL)^2}}$. Since the frequency term f appears in the impedance, it is clear that impedance varies with frequency as well as with resistance and inductance. The current lags behind the voltage by an angle ϕ which has a value such that $\tan \phi = \dfrac{2\pi fL}{r_p + R_0}$.

If the plate circuit contains a load having a resistance R_0, an inductance L and a capacity C the current is

$$I_p = \frac{uE_g}{\sqrt{(r_p + R_0)^2 + \left(2\pi fL - \dfrac{1}{2\pi fC}\right)^2}}$$

and the phase angle ϕ is given by

$$\tan \phi = \frac{1}{r_p + R_0}\left(2\pi fL - \frac{1}{2\pi fC}\right).$$

These equations state that, for a given value of impressed grid voltage, the alternating plate current may be considered to have the same value and phase relations as a current flowing in a circuit having a resistance r_p, an impedance Z, and an applied voltage of μE_g.

When the plate circuit contains reactance as well as resistance the phase difference between the plate and grid voltages may not be 180 degrees. Thus, consider a load having an impedance Z made up of a resistance R_0 and a reactance X_0. If the plate current is represented by I_p, as in Fig. 113, then

the voltage drop I_pr_p in the tube is located as OY, the drop I_pR_0 in the external resistance is YS, and the drop I_pX_0 in the external reactance is ST, located at right angles to the axis. Then, the drop I_pZ in the external impedance is YT, the resultant of the resistance drop I_pR_0, and the reactance drop I_pX_0. The impressed voltage uE_g in the plate circuit is given by OT and is the resultant of the voltage drop I_pr_p in the tube and the external impedance drop I_pZ. When the external impedance is equal to the plate resistance, that is, when OY equals YT in Fig. 113, the angle has a value of 45 degrees.

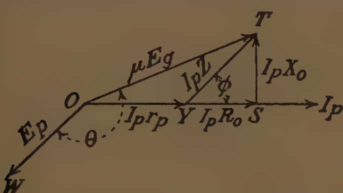


FIG. 113.—Typical vector diagram showing relation between plate currents and voltage drops in external resistance and inductive reactance.

FIG. 114.—Typical vector diagram showing relation between plate currents and voltage drops in external resistance and capacity reactance.

Also, E_p is equal to $-I_pZ$ and is represented in the diagram by OW which is parallel to I_pZ or YT. The angle θ which represents the phase difference between E_p and uE_g or E_g has a value of 157 degrees.

The phase difference between E_p and I_p is given by the angle whose value is such that its tangent is X_0/R_0, while that between uE_g and I_p is $\frac{X_0}{r_p + R_0}$.

Now, if the reactance X_0 were a capacity, the voltage drop I_pX_0 would be drawn in a direction vertical to I_p but downward, instead of upward as in Fig. 113 in which I_pX_0 is taken as an inductive reactance. The resulting relations would then be represented as in Fig. 114.

Voltage Amplification.—In the simple case in which the external load consists of a resistance R_0 the alternating voltage drop across R_0 is, $I_pR_0 = \frac{uE_g}{r_p + R_0}$. The ratio of this alternating voltage which operates in the plate circuit to the alternating

grid voltage is the voltage amplification, usually expressed as $A = \frac{uR_0}{r_p + R_0}$. When a tube is in use as a voltage amplifier, maximum amplification is obtained by making the load resistance as high as is practical. This becomes evident from a consideration of the above equation for A. That is, with very high load resistances the term r_p becomes negligible and the voltage amplification approaches the amplification factor u of the tube.

When the external load consists of an inductance and if the resistance R_0 of the reactance coil is small compared to r_p and wL, then the voltage across the output circuit is $V = I_p wL = uE_g \frac{wL}{\sqrt{r_p^2 + (wL)^2}}$. The voltage amplification $\frac{V}{E_g} = \frac{\mu wL}{\sqrt{r_p^2 + (wL)^2}}$ may be made nearly equal to u if wL is large. The "B" battery voltage need not be greater than the rated plate voltage of the tube because the resistance of the coil is assumed to be negligible.

Maximum Power Output.—The voltage amplification may be considered as the load voltage drop per volt input since

$$\frac{uR_0}{r_p + R_0} = \frac{uE_g}{r_p + R_0} \times \frac{R_0}{E_g} = \frac{I_p R_0}{E_g}.$$

The current output per volt input is $\frac{I_p}{E_g} = \frac{u}{r_p + R_0}$. The product of these two expressions gives the power output per volt squared of the input as $\frac{I_p R_0}{E_g} \times \frac{I_p}{E_g} = \frac{I_p^2 R_0}{E_g^2} = \frac{u^2 R_0}{(r_p + R_0)^2}$. It can be shown by differentiating this equation that the condition for *maximum* power output occurs when $R_0 = r_p$, that is, when the load resistance is equal to the plate resistance of the tube. It is important to remember that this result is obtained by considering the tube as a generator and neglecting the effect of distortion which modifies the relations considerably.

Effect of Phase Relations on Maximum Power Output.—The power output of a tube is a maximum when the current and voltage are in phase and is equal to one-half the product

of the normal plate voltage and the normal plate current. In order to obtain a phase relation of this kind, the load of the plate circuit must consist of resistance only of a value equal to the tube plate resistance.

Types of Amplifiers.—An amplifier is usually made up of a number of tubes and associated apparatus. Each tube and its related devices is considered as one stage. The apparatus is arranged in such a way that the fluctuating plate current of the tube in the first stage produces a fluctuating voltage which acts on the grid circuit of the tube in the second stage. The fluctuating plate current of the tube in the second stage, in like manner, is passed on to that in the third, and so on. The plate circuit of the tube in the last stage contains the sound-producing device such as a loud speaker. The method of coupling one stage to the next determines the different types of amplifiers, for either radio-frequency or audio-frequency use. These types are the resistance-coupled amplifier, the inductance-coupled amplifier, and the transformer-coupled amplifier.

The vacuum tube with its associated apparatus may be used as an amplifier in radio-frequency amplification in which the incoming high-frequency currents and voltages are amplified before detection, or it may be used in audio-frequency amplification in which the *detected* currents and voltages are amplified. Although the methods of constructing such amplifiers are similar, the values of the constants differ so that the apparatus is not interchangeable.

AUDIO-FREQUENCY AMPLIFICATION

Resistance Coupling.—A circuit diagram of a resistance-coupled audio amplifier is shown in Fig. 115. An incoming signal voltage produces a current through the resistance R_1 in the plate circuit of the detector tube. Voltage variations across R_1, diminished by any drop caused by the blocking condenser, are impressed on the input circuit of the first audio-frequency tube. Grid voltage variations of the first audio-frequency tube cause corresponding variations of plate voltage across the resistance R_2 which are impressed on the

input circuit of the second audio-frequency tube. The voltage variations are relayed in a similar manner by the second and third audio-frequency tubes, and are finally impressed on the loudspeaker circuit.

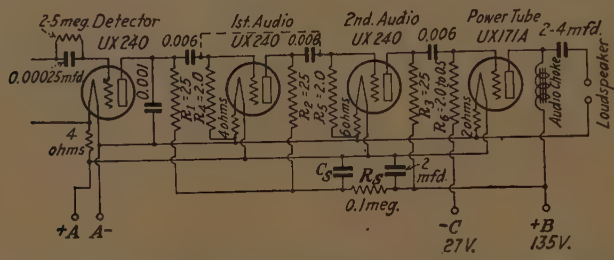


FIG. 115.—Circuit diagram of resistance-coupled audio amplifier.

The blocking condensers are necessary to insulate the grids of the audio-frequency tubes from the high positive voltage of the "B" battery. Because the grids are thus isolated they would tend to accumulate negative charges. To prevent this

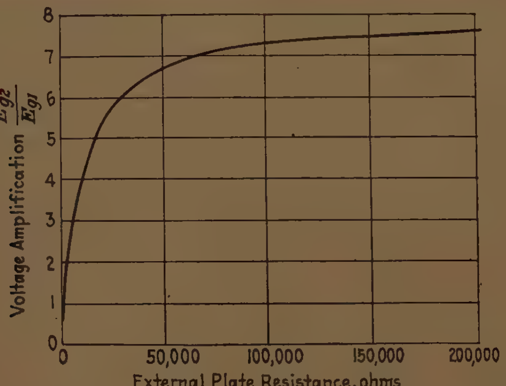


FIG. 116.—Theoretical relation of voltage amplification to load resistance for UX-201A tube.

accumulation, a high-resistance leakage path is provided through the grid leaks R_4, R_5, R_6, which ordinarily have a resistance of the same magnitude as that of the internal grid-filament resistance of the tube.

Size of Coupling Resistance.—A consideration of the relation for voltage amplification $\frac{E_{g2}}{E_{g1}} = \frac{uR_0}{r_p + R_0}$ shows that the voltage amplification increases as R_0 increases. When R_0 is so large that r_p may be neglected, the value of voltage amplification reaches its maximum value, $Eg_2/Eg_1 = u$.

The theoretical relation between voltage amplification and load resistance for a UX-201A tube with an amplification factor of 8 and a plate resistance of 10,000 ohms is shown in Fig. 116. The gain in amplification for resistances greater

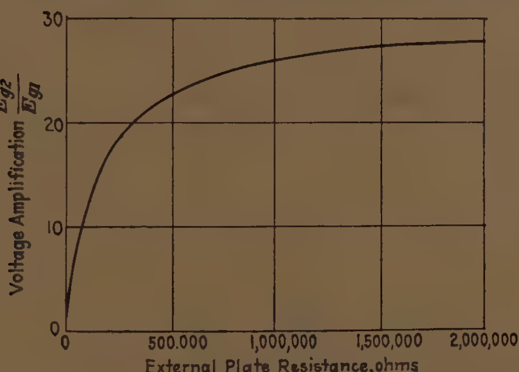


FIG. 117.—Theoretical relation of voltage amplification to load resistance for UX-240 tube.

than 50,000 ohms is small. It is necessary to remember that when the plate circuit is loaded with a resistance the battery voltage must be increased to compensate for the drop in the resistance. From Fig. 117 it is seen that the increase in amplification of a UX-240 tube with an amplification factor of 30 and a plate resistance of 150,000 ohms is small for resistances greater than 500,000 ohms.

Size of Grid-leak Resistance.—If the grid-leak resistance is too high the tubes may become temporarily inactive. A low grid-leak resistance, on the other hand, reduces the amplification; that is, when the grid-leak resistance is low, the total impedance of the input circuit of the stage is decreased, the voltage drop across the coupling resistance is reduced, and

the amplification is cut down. Hence the value of grid-leak resistance should be less than the value which will permit the tubes to "block."

Size of Blocking Condenser.—Several factors are involved in the determination of the size of a blocking condenser, and the final choice is a compromise among them. The rapidity with which the condenser responds to voice amplitude variations requires that the *time constant* $R \times C$ be small, where C is the capacity of the blocking condenser and R the grid-leak resistance. In order to make $R \times C$ small, C must be as small as possible for the reason that if R is decreased it causes such a reduction in the impedance of the grid-filament circuit that the voltage drop across the coupling resistance is diminished and the amplification is reduced.

The reactance of the grid condenser acts to reduce the voltage across the coupling resistance and thus diminishes the voltage available in the grid-to-filament circuit. The reactance of the grid condenser must be small compared with that of the circuit from grid to filament. This circuit is made up of the capacity and resistance of the grid to filament, and the grid-leak resistance. At audio frequencies, the impedance of the path from grid to filament consists mostly of the grid-leak resistance in parallel with the grid-to-filament resistance of the tube and has a resistance of several hundred thousand ohms. This impedance is affected only a little by the reactance of the capacity of the grid-to-filament circuit which may be equal to about a million ohms.

Use of Tubes Having High Amplification.—With resistance coupling, the amplification is practically dependent on the tube alone and the resistances decrease that slightly. Flat frequency characteristics may be obtained with ordinary tubes but the stage amplification is so low that three stages are necessary. It is, therefore, desirable to use tubes having as high an amplification factor as is practical for this service. When UX-240 tubes are used, two stages afford ample amplification. The UX-240 tube has an amplification factor of 30 and about 60 per cent of this, or 20, may be realized in voltage amplification per stage. This value is approximately equal

to the usual transformer stage in this respect. The UX-200A tube is recommended as a detector for use with two stages of resistance coupling and the UX-240 tube for three stages of resistance coupling. When a UX-240 tube is used as a detector, no separate detector "B" voltage tap is required if the resistance shown in the detector-plate circuit of Fig. 115 is used.

Effect of Frequency on Amplification.—One of the advantages of resistance coupling is the good response obtained at very low audio frequencies. The frequency range over which uniform response is obtained may be brought to as low a frequency as may be desired in practice by using the proper size of blocking condenser. When a blocking condenser with a capacity of 0.006 mfd. is used, the range of response is extended so that it is as low as 30 cycles, but the response of the ordinary loud speaker below 50 cycles is not satisfactory. The frequency characteristic begins to drop at about 5,000 cycles because of the high effective input capacity caused by the reaction of the plate load upon the input circuit of the vacuum tube in the amplifier. But even at 10,000 cycles the decrease in amplification is only moderate.

The good response obtained at very low audio frequencies, however, increases the possibility of trouble from a common plate-voltage supply. The by-pass condensers ordinarily used are not very effective at very low audio frequencies, and therefore the common voltage supply acts as a coupling between the stages. This coupling, due to common voltage supply, gives rise to oscillations in the amplifier called "motor-boating." Such action may be avoided by using a low-resistance grid leak across the input circuit of each stage, or by using a smaller blocking condenser. These changes, however, reduce amplification on low frequencies.

If the capacity of the blocking condenser is such that its reactance at low frequencies is of a magnitude which approaches that of the grid leak the amplification is diminished.

Impedance Coupling.—The impedance-coupled audio amplifier uses coils, or a combination of coils and condensers in parallel, in place of the coupling resistances as shown in Fig.

115. A diagram of an impedance-coupled amplifier is shown in Fig. 118. Its action is similar to that of the resistance-coupled amplifier. The coupling must have a high reactance at the frequency for which the amplifier is intended, and a low resistance to a direct current. The advantage of impedance coupling over resistance coupling is that the battery voltage does not have to be increased to compensate for the voltage drop in the coupling unit.

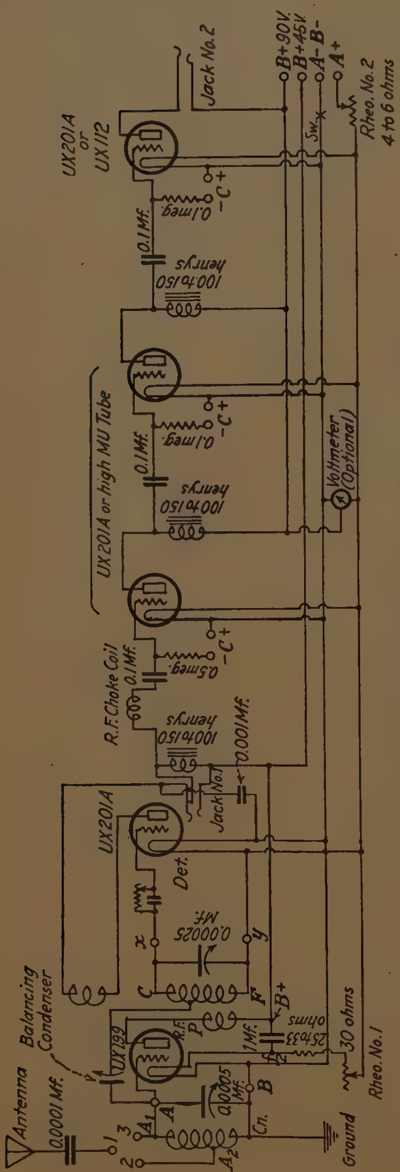


FIG. 118.—Circuit diagram of impedance-coupled amplifier.

Size of Impedance.—If the resistance of the coupling unit is assumed to be negligible, the expression for voltage amplification is given as $\frac{E_{g2}}{E_{g1}} = \frac{ux_0}{\sqrt{r_p^2 + X_0^2}}$ where X_0 is the reactance of the unit at a stated frequency. The curves in Figs. 119 and 120 show the theoretical relation between voltage amplification and the reactance of the coupling unit. With the UX-201A vacuum tube there is not much gain in

amplification at reactances greater than about 30,000 ohms. At a frequency of 50 cycles the inductance of a 30,000 ohm reactance is nearly 100 henrys. Likewise, with the UX-240 tube there is not much amplification beyond a 400,000 ohm reactance which has an inductance of almost 1,250 henrys at 50 cycles. An inductance unit for audio-frequency work is made with an iron core and must have low iron losses and small internal capacity.

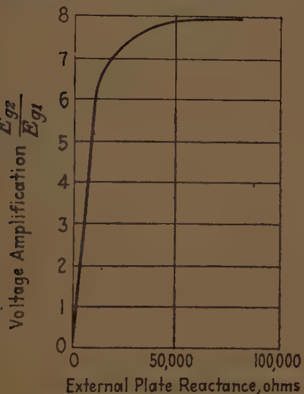


FIG. 119.—Curve showing variation of voltage amplification with external plate reactance for UX-201A tube.

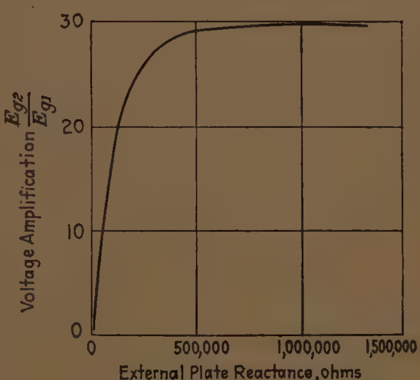


FIG. 120.—Curve showing variation of voltage amplification with external plate reactance for UX-240 tube.

Size of Blocking Condenser and Grid Leak.—The precautions mentioned with regard to the size of blocking condensers and grid leaks for a resistance-coupled amplifier apply also to an impedance-coupled amplifier. It may be stated here that the resistance type of grid leak may in general be replaced to advantage by the inductance type of grid leak. An inductance leak is made with a large value of inductance but a comparatively low resistance, and, therefore, the accumulated charge can leak off the grid in a shorter time than if a resistance type of grid leak is used.

Effect of Frequency on Amplification.—The frequency characteristic obtained with impedance coupling is a curve which is almost as flat as a similar curve for resistance coupling.

Here, also, as in the case of resistance coupling, the only voltage amplification obtained from the circuit is due to the amplifying action of the tube. Three stages of amplification are necessary with tubes such as UX-201A and two stages with UX-240 tubes.

When UX-240 tubes are used the choke coils must be carefully designed to avoid certain difficulties. The low impedance of the choke coil compared with the high resistance of the tube, which is about 75,000 ohms in this case, may result in reduced amplification at low frequencies. The high effective capacity of the input circuit of the tube together with the inductive reactance of the coil may result in resonance, or in extreme amplification, or even in oscillations at frequencies from 100 to 300 cycles per second. The high effective capacity of the input circuit of the tube may cause a marked decrease in amplification at high frequencies.

Transformer Coupling.—The use of transformer coupling in audio-frequency amplification is illustrated in Fig. 121. The alternating voltage of the radio signal which reaches the grid circuit of the detector tube D produces in the plate circuit of that tube a pulsating current. This current flowing through the primary of transformer T_1 induces a stepped-up voltage in the secondary which is applied to the grid circuit of the first amplifier tube A. The variations of this stepped-up voltage are amplified reproductions of the grid-voltage variations which were impressed on the detector tube. The second amplifier tube B further amplifies the alternating voltage, which has been stepped up, through the action of the second transformer T_2. For audio-frequency work it is customary to use iron-core transformers which may be obtained with various step-up ratios from 1:2 to 1:6.

Voltage Amplification.—An elementary study of the transformer action between tube A and tube B in Fig. 121 can be made when certain assumptions are made. The tube capacity between grid and filament, and between plate and filament, which are very small except at high audio frequencies, are neglected. The transformer is assumed to be perfect, that is, it has no leakage or magnetizing current. Also it is assumed

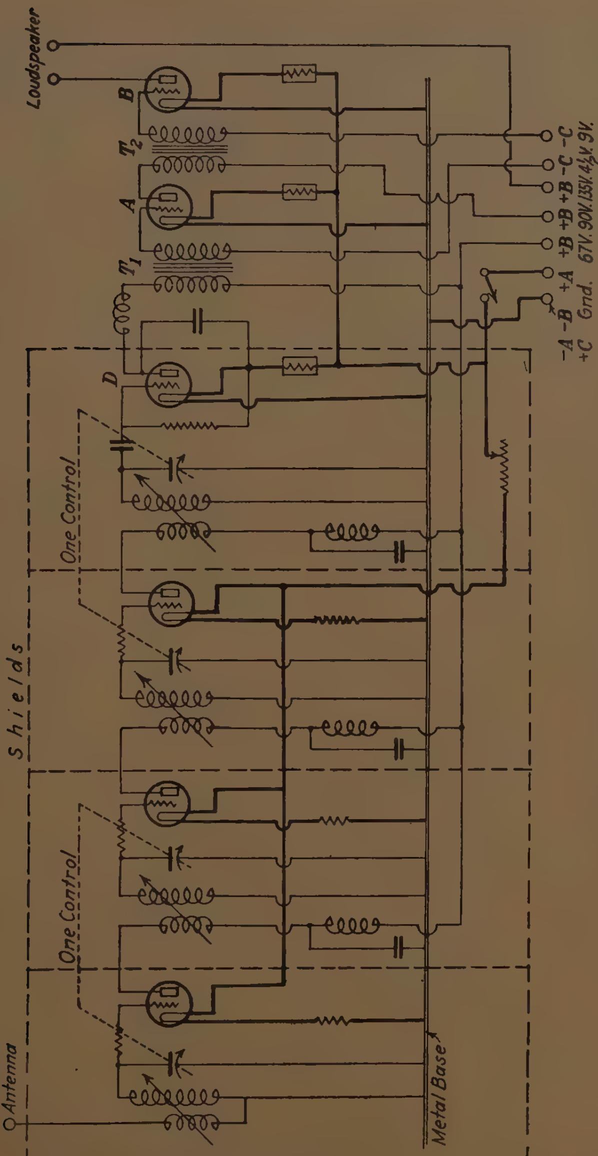


FIG. 121.—Hammerlund-Roberts radio receiver.

that the load on the transformer secondary consists of a non-inductive resistance equal to the grid-filament resistance r_g of the tube B. The portion of the amplifier under consideration is shown in Fig. 122. For a study of the action of such a circuit on alternating current the transformer may be considered as an equivalent resistance[1] in the primary circuit and equal to the resistance r_g of the secondary circuit divided by n^2 where n is the transformer voltage ratio. The voltage acting on the plate circuit of tube A is taken as uE_g. It is then possible to represent the plate circuit of tube A as in Fig. 123. The relation of the voltage E_{t2} in Fig. 123 to uE_g is the same as

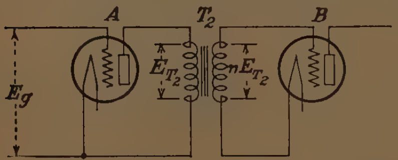


FIG. 122.—Circuit of amplifier in radio receiver in Fig. 121.

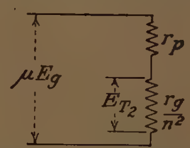


FIG. 123.—Equivalent of plate circuit of tube A in radio receiver in Fig. 121.

that of the equivalent resistance r_g/n^2 to the total resistance $r_p + \frac{r_g}{n^2}$. That is, $E_{t2} = E_g \frac{ur_g}{r_g + n^2 r_p}$. Since nE_{t2} is the voltage acting on the grid of the tube B the voltage amplification is equal to $\frac{nE_{t2}}{E_g} = \frac{unr_g}{r_g + n^2 r_p}$. From this expression it is seen that the voltage amplification depends directly upon u and that as r_g increases the voltage amplification increases, approaching un as a limit. Therefore, r_g should be made as large as possible by keeping a negative bias on the grid. In practical applications, r_g is equal to about a million ohms but under certain conditions of operation may have a value of only a few hundred thousand ohms. Further, the expression for voltage amplification has a maximum value when $n = \sqrt{r_g/r_p}$ which indicates the best value for the transformer ratio. The voltage amplification, in terms of this value of n, is $un/2$. Both the voltage amplification and the transformer ratio,

[1] If secondary current $I_s = nE_{t2}/r_g$ and primary current $I_p = nI_s$, then $I_p = n^2 E_{t2}/r_g$.

however, are decreased by imperfections in an actual transformer.

Transformer Construction.—The greater the primary impedance relative to the plate impedance the larger will be the voltage impressed on the primary coil of a transformer, and consequently, also the amplification. A primary inductance of 100 henrys has an impedance of 628,000 ohms at 1,000 cycles and 62,800 ohms at 100 cycles, which is about six times the plate resistance of the tube. The reduction of impedance with frequency decreases amplification at low frequencies. The primary inductance depends upon the number of primary turns, the cross section of the core, the length of the iron core path, and the amount of direct current flowing in the primary. High core losses diminish the amplification at all frequencies. The voltage amplification increases rapidly with an increase of the primary no-load reactance at low values, but more slowly at higher values. Beyond a certain point, then, there is little to be gained by increasing the reactance. The factors of size and cost must be considered, also, for an increase in the core increases the size of the unit, and if more primary turns are used, more secondary turns are necessary for a given value of n.

Since the primary and secondary coils cannot occupy the same space there is a certain amount of magnetic flux called "leakage flux" which does not link both coils. This produces the leakage inductance which decreases amplification at all frequencies.

The capacity effect between turns and between layers is small and affects amplification only at the higher frequencies. The capacity effect between the primary coil and the secondary coil also acts as a short circuit at the higher frequencies and tends to decrease amplification.

If the transformer ratio n is made high, and there are many turns on the primary, a large number of turns are needed on the secondary. This results in an increased internal capacity effect which, with the input capacity of the next tube, brings the natural frequency of the secondary circuit within the range of audio frequencies and causes a resonance peak. Amplification beyond this natural or "cut-off" frequency is very poor.

It has been shown that amplification of low frequencies requires a large number of primary turns and that a large number of secondary turns diminishes the amplification of

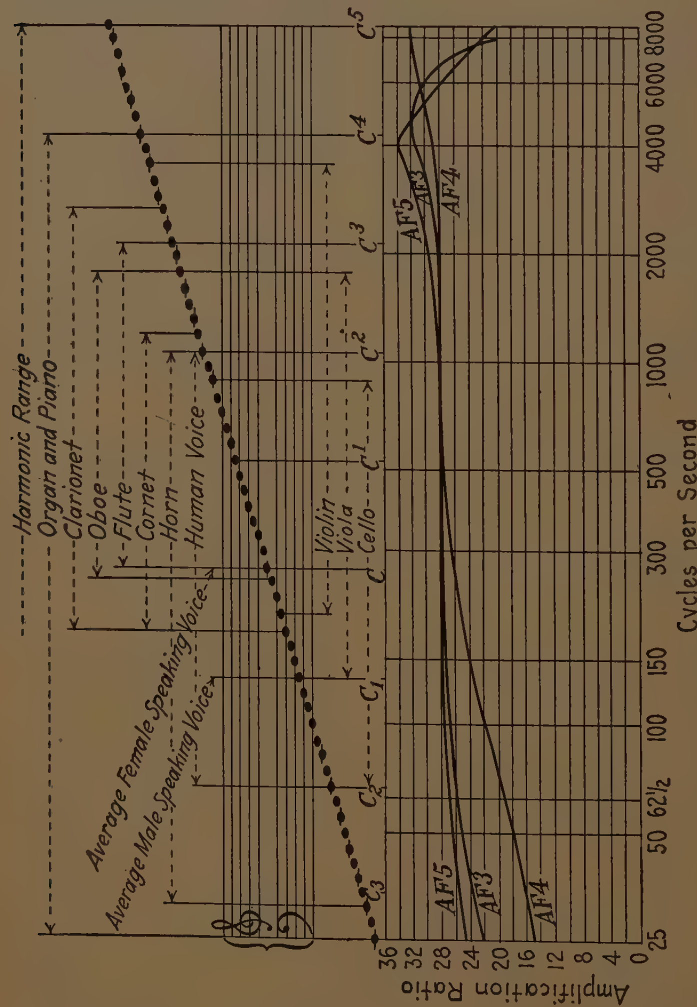


FIG. 124.—Amplification curves of audio-frequency transformers.

high frequencies. Consequently the transformer is made with a rather low ratio, a core having a large cross section, low internal capacity, and a low leakage inductance.

Amplification Curves.—The performance of a group of modern transformers is shown in Fig. 124. A UX-112A vacuum tube was used and was operated with a plate voltage of 68 and a grid bias of −3 volts. The specifications for the several types of transformers are given in the following table.

Type	Ratio n	Maximum primary current, milliamperes	Resistance		Inductance, no direct current		Primary inductance with 3 milliamperes direct current
			Primary, ohms	Secondary, ohms	Primary, henrys	Secondary, henrys	
AF5	1:3.5	10	2,400	34,000	190	2,330	110
AF3	1:5	5	1,375	26,000	95	2,330	55
AF3	1:3.5	5	1,900	26,000	190	2,330	85
AF4	1:3.5	5	950	8,900	42	515	35

The effect of the lower primary impedance of the AF4 transformer is indicated by the decrease in amplification at low frequencies. Both the AF3 and the AF4 transformers "cut off" at about 8,000 cycles. The small resonance peaks are due to the effect of internal capacity and leakage inductance.

The effect of a strong radio signal is to reduce amplification. This occurs because a strong signal causes an increased current to flow in the grid circuit. This current flows through the secondary winding of the transformer and acts so as to reduce the voltage developed.

A condition of resonance at 5,000 cycles or more does not produce a very noticeable effect on reception because the efficiency of the loud speaker at such frequencies begins to drop off. A condition of resonance at moderately low frequencies may be detected by laboratory measurements but, if small, does not perceptibly affect the performance of the amplifier.

The performance of a multi-stage amplifier may differ considerably from the frequency characteristic of a single transformer. Interstage coupling may increase the effect of resonance conditions, and the coupling resulting from a

common plate voltage supply may cause a considerable change in amplification at low audio frequencies.

RADIO FREQUENCY AMPLIFICATION

Advantages of Radio-frequency Amplification.—The efficiency of a detector tube is greater for strong than for weak signals, because the efficiency varies as the square of the signal voltage. An example will serve to illustrate this action. If the amplitude of a radio-frequency signal is increased five times, its amplitude after detection is twenty-five times as great. If two stages of radio-frequency amplification are used, each giving a voltage amplification of 5, the signal amplitude at the input of the detector is twenty-five times as great, and that at the output of the detector, six hundred and twenty-five times as great. Finally, if two stages of audio-frequency amplification are used, each giving a voltage amplification of 5, the total amplification is $625 \times 5 \times 5 = 15{,}625$.

Function of Radio-frequency Amplifier.—The three factors which enter into radio-frequency amplification are (1) sensitivity, (2) selectivity and (3) fidelity of reproduction. Sensitivity measures the extent of the response to signals of the frequency to which the receiver is tuned. Selectivity is the ability of the receiver to differentiate between signals of different frequencies. Fidelity of reproduction is determined by the response of the receiver to the frequency range of the side bands. This is for the reason that when a carrier wave is modulated at audio frequency, these three frequencies are present: (1) the carrier frequency, (2) the carrier frequency plus the audio frequency, and (3) the carrier frequency minus the audio frequency. The last two are called the *sidebands*. If the fidelity is to be good the sidebands must be fully reproduced. The radio-frequency amplifier must select the desired frequency and must amplify the carrier frequency with its sidebands. The resonance curve must not be too sharp at the top or the sidebands will be cut off. On the other hand, if the resonance curve is too broad, interference may be caused by the amplification of other frequencies.

Resistance Coupling.—At high frequencies, such as 500,000 cycles per second (600 meters), the impedance of the grid-to-filament circuit consists largely of the reactance of the grid-filament capacity which may be several thousand ohms. The disadvantage of this is that the capacity reactance of the grid-filament circuit is so small that it has the effect of a short-circuit on the coupling resistance and, therefore, decreases the amplification. The blocking condenser must have a capacity such that its reactance is smaller than the grid-filament capacity reactance as stated above. This shows that the capacity of a blocking condenser for use at high frequencies may be made smaller than that of one for use at low frequencies. A resistance-coupled amplifier for high-frequency work is similar to one for audio frequency, except that the blocking condenser must be smaller. The distributed capacity of the coupling resistance should be as small as possible; otherwise, it would reduce the impedance of the coupling unit and thus diminish the amplification. With ordinary vacuum tubes a resistance-coupled radio-frequency amplifier does not give satisfactory performance on wave lengths below 1,000 meters (300,000 cycles per second). Furthermore, such an amplifier is noisy because it amplifies audio frequencies as well as radio frequencies.

Impedance Coupling.—At 600 meters (500,000 cycles) the inductance of the 30,000 ohm reactance used with a UX-201A tube is 0.01 henry, and that of the 400,000 ohm reactance used with a UX-240 tube is 0.1 henry. It is difficult to build an inductance of this amount without iron so that its internal capacity is small and its size is not large. The difficulty introduced by the distributed capacity is that excessive amplification exists at a frequency equal to the natural frequency of the coupling unit.

The performance of an amplifier using inductance alone is not satisfactory when used for short wave lengths. If a condenser and inductance in parallel are used, they may be tuned to the required frequency. With such a construction the value of inductance may be low because the tuning is accomplished by the condenser, but the impedance of the

unit may be high. Tuned amplification of this kind is especially useful for radio-frequency amplification because of the great selectivity which it provides.

An amplifier of the inductance-coupled type, just as one of the resistance-coupled type, amplifies audio frequencies as well as radio frequencies and hence has no selectivity.

Transformer Coupling.—For radio-frequency amplification it is customary to use air-core transformers (although satisfactory iron-core transformers have been developed) with a 1 to 1 ratio. On very long wave lengths a step-up ratio has been found advantageous.

If two *low-loss circuits* are coupled "loosely" by means of a transformer with a primary of few turns and a secondary of many turns, the voltage amplification is increased because of the step-up ratio and the tube amplification. A circuit of this kind, however, gives maximum amplification at only one frequency and poor amplification at adjacent frequencies. In order to obtain a circuit which gives more uniform amplification than the untuned circuit over a band of frequencies, a variable tuning condenser is used across the transformer secondary. Such a circuit is called a *tuned radio-frequency amplifier.*

Voltage Amplification.—The circuit arrangement of a tuned radio-frequency amplifier is shown in Fig. 121. The equivalent of one of these radio-frequency stages is given in Fig. 125. The expression for the voltage amplification according to the principles and notation of Chap. III is $\dfrac{(2\pi f)^2 M L_1 u}{R_e r_p + (2\pi f M)^2}$.

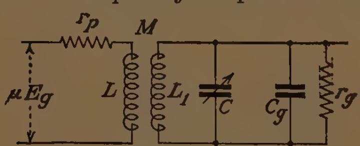


FIG. 125.—Equivalent circuit of radio-frequency stage of radio receiver of Fig. 121.

From this expression it is seen that the voltage amplification varies with the amplification factor (u) of the tube, the secondary inductance (L_1), the coupling (M) between the coils of the transformer, the plate resistance (r_p) of the tube, and the effective resistance of the secondary circuit (R_e). The mutual inductance M between L and L_1 is equal to $k\sqrt{LL_1}$ in which k is the coefficient of coupling. R_e is the

total series resistance of the secondary circuit and is equal to the L_1 coil resistance (3.4 ohms) plus the equivalent resistance of r_g. The equivalent resistance of r_g is $(2\pi fL_1)^2/r_g$. In order to illustrate the use of the expression for voltage amplification assume that $f = 500{,}000$ cycles, $k = 0.3$, $L = 35$ microhenrys, $L_1 = 250$ microhenrys, $u = 8$, $r_p = 10{,}000$ ohms, and $r_g = 1{,}000{,}000$ ohms. Then the equivalent resistance of $r_g = \dfrac{(6.28 \times 500{,}000 \times 250)^2}{10^{12} \times 10^6} = 0.62$ ohms and $R_e = 3.4 + 0.62 = 4$ ohms, approximately. $M = 0.3 \sqrt{35 \times 250} = 28$ microhenrys. The substitution of these values in the expression for voltage amplification gives

$$\frac{(6.28 \times 5 \times 10^5)^2 \times 28 \times 250 \times 8}{\left[4 \times 10^4 + \left(6.28 \times 5 \times 10^5 \times \frac{28}{10^6}\right)^2\right] \times 10^6 \times 10^6} = 11.6.$$

It is important to keep enough negative bias on the grid circuit of the tube so that the resistance r_g of the grid-filament circuit may be high.

Resonance Curve.—The shape of the resonance curve depends upon the effective resistance of the secondary circuit, upon the coupling between the coils, and upon the grid-plate capacity of the tube, which couples the input and output circuits. Increased coil coupling increases the secondary circuit resistance and has the effect of broadening the resonance curve and diminishing the selectivity. Amplification improves as the coupling is increased until the best point is reached, beyond which it slowly decreases. The degree of coupling generally used is well below the best value to obtain stability and selectivity. The tuning of the secondary circuit is broadened at high frequencies.

Because of the grid-plate capacity, the output circuit, under the usual load conditions, reacts on the input circuit. The feed-back action is greater at high frequencies and tends to offset the broadened tuning. The effect is equivalent to the addition of a condenser and resistance across the secondary circuit. The constants of the output circuit determine whether this resistance has a positive or a negative effect. The action of a negative resistance is to offset the losses in the

secondary. When the losses in the secondary circuit are offset in this manner, the tuning is made sharper unless the negative resistance supplies all the losses in which cases the circuit will oscillate.

Tubes for Radio-frequency Amplification.—A tube having a fairly high output resistance may be used efficiently for radio-frequency amplification. The limiting factor as regards the permissible tube resistance is the increase in resistance of the secondary or tuned circuit. Ample voltage amplification, that is, good sensitivity, is obtained with a high-resistance tube which is coupled closely to a tuned secondary, but the selectivity is poor because of the increase in effective resistance of the circuit. A low-resistance tube can be used with less coupling than a high-resistance tube, with improvement in selectivity. But if a low output resistance results from decreasing the amplification factor, the sensitivity is reduced and the drain on the "B" battery is increased.

Methods of Stabilizing to Avoid Oscillation.—There are several methods of stabilizing a circuit so that it will not oscillate. Two common methods are shown in Fig. 126. In one of these methods the grid return is varied by a potentiometer in such a way that a positive bias may be applied to the grid. A current then flows in the grid circuit and has the effect of decreasing the resistance between the grid and filament and increasing the effective resistance of the tuned circuit.

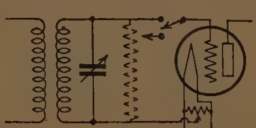


Fig. 126.—Methods of stabilizing circuits by the use of grid bias voltage to prevent oscillation.

The main disadvantages of this method are the heavy plate current which flows when the grid is positive and the increased damping of the tuned circuit. The other method utilizes an adjustable potentiometer, shown by the dotted lines, connected across the tuning condenser. Adjustment of the potentiometer varies the voltage applied to the grid and thus serves as a control of amplification and stability.

A better method than either of the two above is shown in Fig. 127 where the grid circuit has a resistance R of which the value is from 100 to 800 ohms. The decrease in amplification

caused by the use of the resistance R is more pronounced at high frequencies, which is an advantage because the feed-back increases with the frequency. A disadvantage, however, is introduced by the broader tuning due to the greater damping of the circuit.

The insertion of resistance in the "B" plus lead may be used to secure stable operation by lowering the effective plate voltage. The advantages of this method are the saving in "B" battery current when a local station is being received, and the sharper tuning which is possible because there is not much increase in the damping of the resonant circuit.

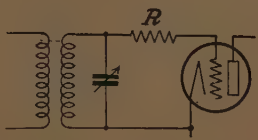


FIG. 127.—Method of stabilizing circuits by use of grid resistance to prevent oscillation.

The best method of obtaining stability is to neutralize the capacity of the tube by means of another capacity. Two ways of connecting this capacity are the Rice method and the Hazeltine method. The Rice method is shown in Fig. 128. The center of the input coil is grounded so that the coils must be carefully arranged. Otherwise, the balance obtainable

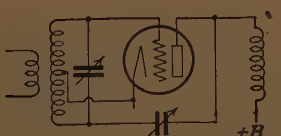


FIG. 128.—Rice method of stabilizing by neutralizing the capacity of a tube by another capacity.

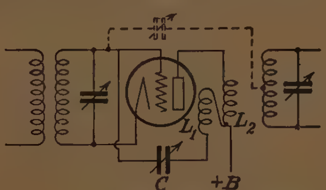


FIG. 129.—Hazeltine method of stabilizing by neutralizing the capacity of a tube.

may be upset by capacity coupling between the coils. The capacity effect may be minimized by increasing the spacing of the coils or by using a shield between the coils. Some decrease in sensitivity may be expected when this circuit is used because the input voltage applied to the tube is half of that obtained across the tuned circuit.

The coils L_1 and L_2 required in the Hazeltine method, shown in Fig. 129, have a double-wound primary which is used to

obtain close coupling. An "alternate" connection may be made by omitting L_1 and connecting the variable condenser C as indicated by the dotted lines. In this case, L_2 must be placed adjacent to the lower portion of the secondary in order to obtain close coupling. Either of the last two methods is nearly independent of frequency over the usual range of frequencies used in broadcasting.

Push-pull Amplifier.—The push-pull arrangement of tubes shown in Fig. 130 is intended to minimize the distortion produced by the harmonics of the radio signal voltage. Tubes used in this way must be "matched" if best results are to be

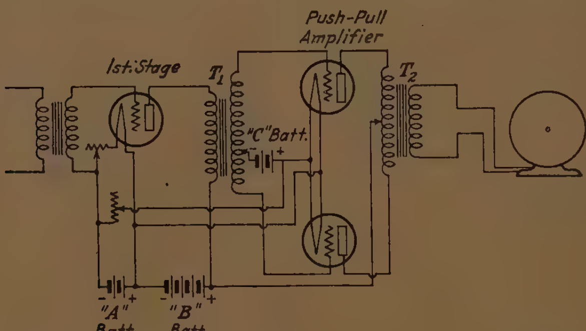


Fig. 130.—Push-pull arrangement of tubes in amplifier.

obtained. The grids of the tubes are biased by means of the "C" battery connected to the mid-point of the secondary of the T_1 transformer. If an alternating current flows in the primary of T_1, one of the grids is positive when the other is negative and *vice versa*. The plate current in one tube is increasing, therefore, while that in the other is decreasing. The secondary windings of the output transformer T_2 are connected in such a way that the resultant plate current is proportional to the difference of the plate currents from the two tubes. The result of this is that the distorting components are balanced and eliminated.

Reflex Amplification.—A system of amplification which was developed to reduce the number of tubes required in a multistage receiver is shown in Fig. 131. The radio signal first

passes through a number of stages of a radio-frequency amplifier, is detected in a separate stage, and is then returned through some of the radio-frequency stages to obtain audio-frequency amplification. Thus, in Fig. 131 the audio component of the detector plate current is returned through an audio transformer to the grid circuit of the third radio-frequency tube. The audio component of the plate current of this tube goes through an audio transformer to the last (audio-frequency) tube and thence to the loud speaker. The

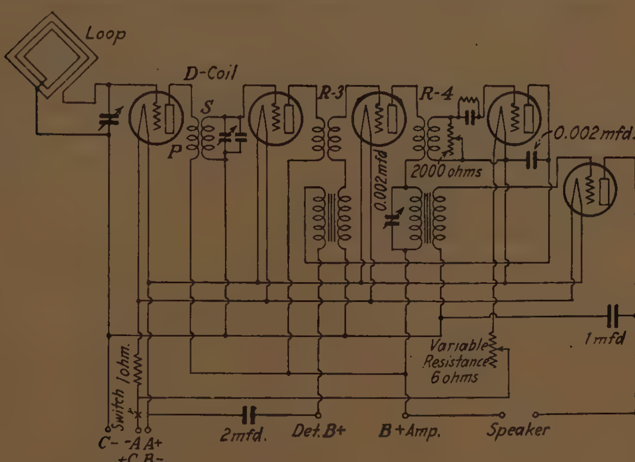


FIG. 131.—Acme five-tube reflex receiver.

five tubes used in this way allow three stages of radio-frequency amplification, a detector stage, and two stages of audio-frequency amplification. It is assumed that a tube is capable of such double duty because of the wide discrepancy in the frequencies involved. This use limits, however, the adaptability of the tube to the reception of high frequencies. Suitable fixed condensers are placed across the audio-frequency transformer windings to by-pass radio-frequency currents. The use of these condensers reduces the transformer efficiency and introduces audio-frequency distortion.

The inverse reflex system was devised to equalize the load on the grids of the various tubes. In a receiver having three

radio-frequency tubes, the audio-frequency plate current is returned to the last or third radio-frequency tube and thence to the second tube. That is, the third radio-frequency tube serves also as the first audio-frequency tube and the second radio-frequency tube serves also as the second audio-frequency tube. Since two stages of audio-frequency amplification are ordinarily used, only two tubes may be eliminated by this method regardless of the number of radio-frequency stages in the receiver.

In reflex amplification, although a tube may perform double duty, the actual overall voltage amplification is less than that obtained with single-duty tubes. Considerable difficulty is usually experienced with reflex receivers in attaining stability.

Superheterodyne Receiver.—It has been shown that the operation of a multi-stage radio-frequency amplifier is effective over only a limited frequency range. In the superheterodyne receiver the high-frequency alternating current of the received signal is transformed into an alternating current of lower radio-frequency, called the "beat" frequency, which is better suited to the amplifier. This transformation is accomplished by combining the received radio current with a locally generated current of suitable frequency. The current having this "beat" frequency goes through a filter and is then amplified in a number of intermediate stages which are tuned to the "beat" frequency. The output of the last intermediate stage is detected and passes through the usual stages of an audio-frequency amplifier. "Beat" frequencies of from 30 to 100 kilocycles have been used. At 50 kilocycles the reactance of the grid-filament capacity of a vacuum tube is high enough so that it causes very little interference with the action of the amplifier.

The first oscillator radiates energy from the antenna unless it is preceded by a properly balanced circuit. In one type of superheterodyne the interference from such radiation is reduced by operating the oscillator so that its second harmonic is used as the locally generated frequency. In this way the amount of radiation is reduced and the frequency of the radiated energy is outside the range of broadcasting.

Number of Stages.—In the types of amplifiers which have been described, the number of stages which can be used is limited. This is due to the fact that the magnetic and electrostatic stray fields developed in the last stage act on the circuits of the preceding stages. Such interaction, together with the internal capacity coupling of the tubes allows a feed-back of the amplified energy to the input circuits which may lead to the generation of oscillations in the amplifier with resultant howling and noises. Special methods may be used to minimize the effect of such feed-back.

Distortion in Power Tubes.—Two causes of distortion will be considered here. First, the distortion due to the curvature of the plate voltage-plate current curves at low values of plate current; second, the distortion resulting from the flow of grid current.

The effect of distortion due to the curvature of the curves is shown by an inspection of the plate voltage-plate current curves in Fig. 132. While these curves do not indicate actual conditions of operation because they are taken with no load in the plate circuit, the procedure outlined below may be used to determine the behavior of tubes with a plate load.

The plate current-plate voltage curves of the UX-171A type for various grid voltages are given in Fig. 132. When a plate voltage of 180 volts is applied, the tube operates along the vertical line at 180. The value of the plate current for a grid bias of −40 volts is found to be 20 milliamperes at the intersection of the vertical line and the "bias" line. Now, if a signal voltage having a peak amplitude of 10 volts is applied to the grid, the range of operation of the plate current is along the vertical 180-volt line from its intersection with the −30 volt "bias" line to that with the −50 volt "bias" line. The positive swing of the grid produces an increase in plate current of 18 milliamperes, but an equal negative swing produces a decrease of only 14 milliamperes. This effect is due to the increased curvature at low plate voltages of the plate current-plate voltage curve, and causes distortion by introducing into the output current a second harmonic component which did not exist in the impressed signal voltage. The effect of the

curvature increases rapidly as the amplitude of the signal voltage is increased. At low values of plate current the curvature is much greater, and, therefore, the instantaneous value of plate current must not come close to zero. Under the load conditions given in the following paragraphs, the minimum value of instantaneous plate current for satisfactory reproduction is taken to be 1.0 milliampere. This is indicated by the dotted line at the bottom of Fig. 132.

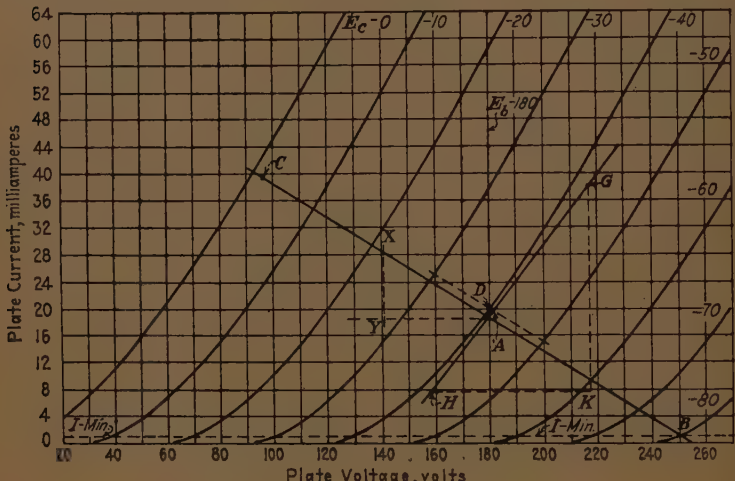


FIG. 132.—Curves showing the effect of distortion.

When the load resistance is very high, the range of plate current is no longer on the vertical voltage ordinates, and the line representing the conditions of operation is then swung, about the "operating point," away from the vertical, until it is nearly parallel to the 20 milliampere line. This new line of operation intersects all of the equidistant curves at the same angle so that it is clear that the distortion due to the curvature of the characteristic curve is eliminated. The power output, however, is decreased and approaches zero in the limiting case.

When the load resistance is lower than in the preceding case, an intermediate condition obtains. This may be shown graphically by drawing the "load line" for a given load resist-

ance in the plate circuit. Thus in Fig. 132 the line CAB represents operation at a grid bias of -40.5 volts with a plate load of 3,900 ohms. This "load line" is located by the "operating point" and has a slope equal to the reciprocal of the load resistance. If this figure had been made with a scale of ordinates in amperes, the slope of the "load line" would be given by 1/3,900, and for a milliampere scale the slope becomes 1,000/3,900 or $^{10}\!/_{39}$. If one point A on the "load line" is known, any other point X may be located by using this value of the slope, by the method of drawing through A a horizontal line AY equal to 39 on the scale of abscissas, and at Y drawing a vertical line YX equal to 10 on the scale of ordinates. Then through the points A and X the required "load line" CAB can be drawn.

In the first part of this discussion the distortion occurring with no plate load was shown for operation with -40 volts of grid bias. The effect of the plate load of 3,900 ohms in decreasing this distortion is evident from a consideration of the "load line" through the point D at -40 volts. With no plate load a 10-volt radio signal causes the plate current to range from 18 milliamperes in one direction to 14 milliamperes in the other. The same signal voltage along the 3,900-ohm "load line" causes a range of plate current of 5 milliamperes in each direction. This shows that under these operating conditions the effect of the second harmonic is not appreciable.

The second cause of distortion mentioned previously is that due to a flow of current in the grid circuit. It has been shown that the distortion resulting from the negative swing of the grid voltage on the lower portion of the characteristic having a considerable curvature is eliminated by using a very high plate-load resistance. If, however, the impressed grid voltage is too high it may cause a swing which extends beyond the curve for $E_c = 0$ in Fig. 132. When this happens a grid current flows. As the grid becomes more positive the grid current increases quite rapidly and the grid-to-filament resistance of the tube is decreased. This decrease, however, occurs only when the grid swings positive and, consequently, a very uneven load results on the transformer; this unevenness

of the load produces distortion. The conditions of operation should be such that the grid is always negative with respect to the filament.

Maximum Power Output.—The conditions for maximum power output are limited by the extent to which the output is considered as undistorted. The two forms of distortion treated above must be quite severe in order to affect the quality of reproduction so that it is perceptible to the listener. A distortion of 5 per cent is quite imperceptible to the listener and, hence, may be allowed, especially because only a relatively small power increase is obtained if the distortion is greater. Undistorted power output, then, may be considered as the amount of power which is obtained when the input signal voltage does not become greater than the value producing a 5 per cent distortion due to the introduction into the power output of harmonics of the second and higher degrees.

It has been shown that the power output is a maximum when the resistance of the external load $R_0 = r_p$ the plate resistance of the tube. In this explanation, however, the distortion which is introduced is neglected. To avoid excessive distortion the grid "swing" must be limited, that is, the minimum value of plate current must be greater than 1 milliampere.

Investigations[1] indicate that a maximum undistorted power output is obtained when the load resistance $R_0 = 2r_p$, with the plate and grid voltages adjusted to their best values. The maximum may occur at a different relation between R_0 and r_p if the applied voltages are not set to the best values. That is, the best load is found to have a certain value at a given plate voltage; now, if the grid bias is reduced in order to allow a moderate decrease in plate voltage without a sacrifice in output, the best value of the load is less than that found before. This is shown in Fig. 133 in which the maximum output of the UX-120 tube is found at R_0 = 6,500 ohms, that is, $R_0 = r_p$. The grid-bias voltage for the UX-120 tube at 135 volts is 22½ volts. With this value, the battery voltage may fall to 120 volts before the output is affected very much. At

[1] *Proc. Physical Society* (London), Vol. 36.
Proc. Institute of Radio Engineers, Vol. 14.

120 volts the best load is found to be $R_0 = 2r_p$. If a grid bias of more than 22½ volts is used with a plate voltage of 135 volts a greater power output than that shown in Fig. 133 may be obtained with the higher load resistance. The relations between power output and load resistance for the UX-112A and UX-171A tubes also are shown in Fig. 133.

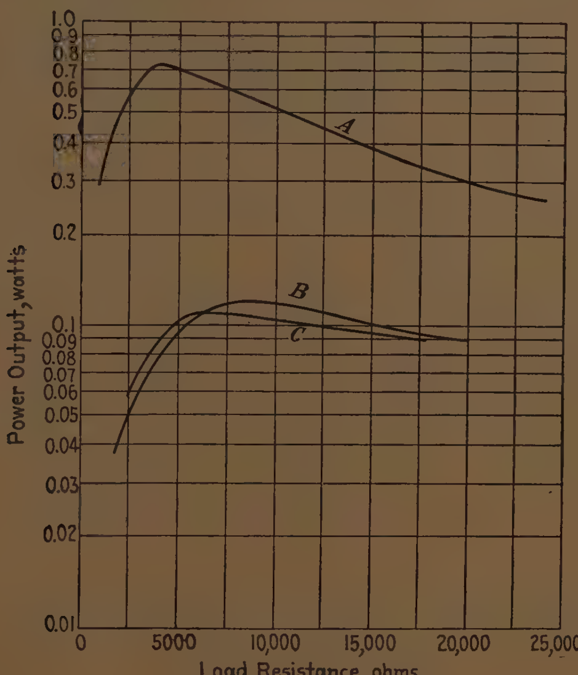


FIG. 133.—Variation of power output with load resistance. Curve "A" for UX-171A tube with grid bias −40½ and "B" battery voltage 180 volts. Curve "B" UX-112A tube with grid bias −9 and "B" battery 135 volts. Curve "C" UX-120 tube with grid bias −22½ and "B" battery 135 volts.

Determination of Power Output and Distortion.—For a UX-171A tube the maximum plate voltage to be supplied is 180 volts and the grid bias is −40.5 volts. Determinations of the best load, the power output, and the second harmonic distortion may be made from the curves in Fig. 132.

The value of 3,900 ohms for the load was taken after a consideration of the plate resistance of the tube. This tube

resistance may be read directly from the curve of plate resistance against grid-voltage at a plate supply voltage of 180 volts, or it may be obtained from the slope of the plate current-plate voltage curve at point A. The tube resistance at the operating conditions represented at A is equal to the reciprocal of the slope of the curve at A. To get the curve slope at A, a line GH is drawn through A parallel to a tangent to the curve for $E_c = -40$. If a triangle such as HGK is constructed, the slope of the curve is given by GK/HK and the reciprocal of the slope, or the tube resistance, is HK/GK. Numerically, this tube plate resistance is equal to $\frac{216.5 - 158.5}{0.038 - 0.008}$ or 1,950 ohms. A load resistance of twice the tube resistance is equal to 3,900 ohms.

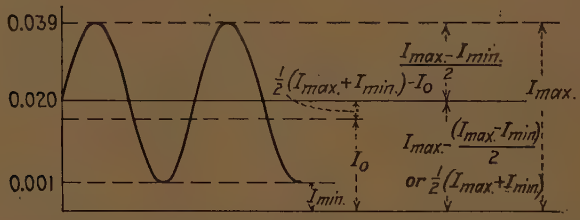


FIG. 134.—Graphical representation of the factors determining distortion in tubes.

The power output is equal to the product of the effective values of the alternating plate voltage and the alternating plate current. These values are determined by the intersection of the "*load line*" CAB with the line of minimum plate current. Thus in Fig. 132 the "load line" intersects the line for minimum plate current at the point B which falls on the curve for $E_c = -80$ volts. This corresponds to a *maximum* negative grid swing of $80 - 40.5$ or 39.5 volts. A positive swing from point A would extend to point C on the curve for $E_c = -1$ volt, as $40.5 - 39.5 = 1.0$ volt. The fluctuating plate voltage as defined by these voltage limits has a value of 250 volts at the point B and 96 volts at point C. The alternating component of this fluctuating voltage has an amplitude

of $\frac{250 - 96}{2}$ or 77 volts, and an effective value of 0.707 × 77 or 54.4 volts. The fluctuating plate current defined by these limits has a value of 0.001 ampere at B and 0.039 ampere at C. Its *alternating component* has an amplitude of $\frac{0.039 - 0.001}{2}$ or 0.019 ampere, and an effective value of 0.0134 ampere. Therefore, the power output, which is the product of the effective values of voltage and current is equal to 54.4 × 0.0134 = 0.73 watts or 730 milliwatts.

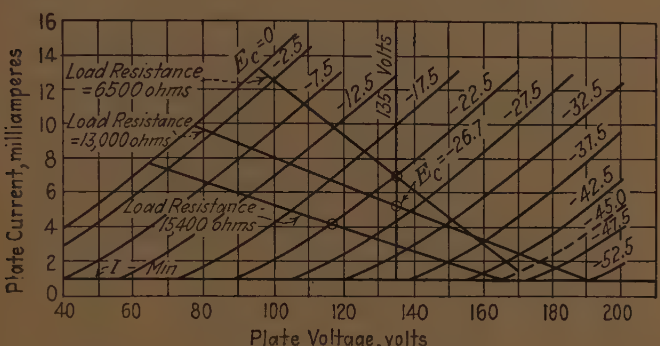


FIG. 135.—Curves for calculating power output for UX-120 tube.

The second harmonic distortion depends upon the difference between the average fluctuating current and the steady plate current. It may be stated as a percentage of the fluctuating plate current by the expression,

$$\text{Distortion} = \frac{\frac{1}{2}(I_{\text{max}} + I_{\text{min}}) - I_0}{I_{\text{max}} - I_{\text{min}}}.$$

The meaning of the various terms in this equation is shown in Fig. 134. Numerically, the distortion $= \frac{\frac{1}{2}(0.039 + 0.001) - 0.0185}{(0.039 - 0.001)} \times 100 = 3.9$ per cent. There are several ways of reducing this distortion, such as decreasing the input signal voltage, increasing the load resistance, or slightly decreasing the grid-bias voltage and at the same

time reducing the input voltage. Such changes, however, also reduce the power output.

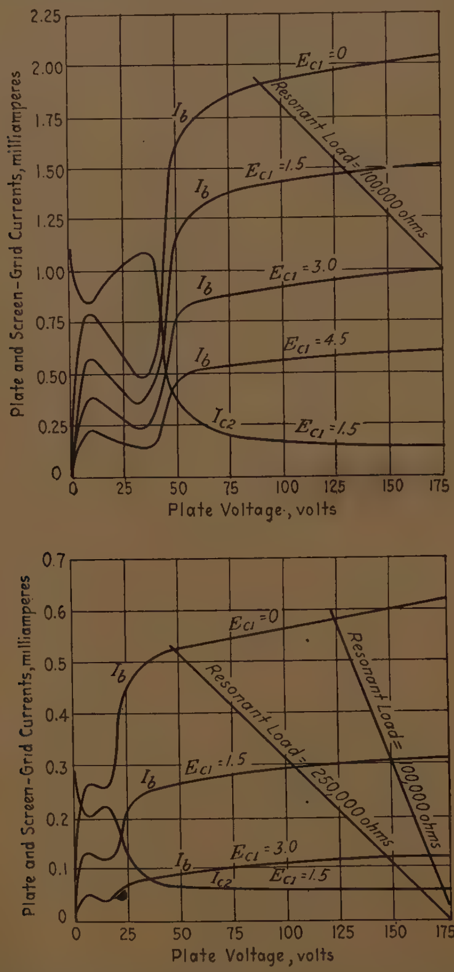


FIG. 136.—Curves for calculating power output for UX-222 tube for grid-screen voltage +45 volts and also + 22½ volts.

The maximum undistorted power output of a number of tubes in common use is given in the accompanying table (p. 196).

The calculations of output characteristics for other types of tubes such as the UX-120, UX-222, UX-201A, and UX-112A may be made from groups of curves showing the variations of plate current with plate voltage as in Figs. 135, 136, 137, and 138.

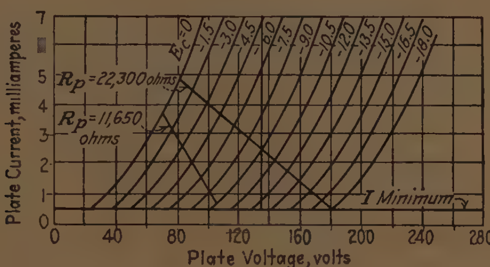


Fig. 137.—Curves for calculating power output for UX-201A tube.

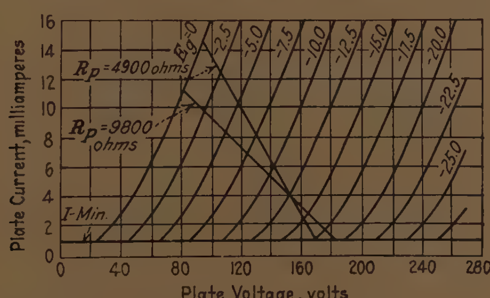


Fig. 138.—Curves for calculating power output for UX-112A tube.

Voltage Amplification of High-resistance Vacuum Tubes.—The curves showing the variations of plate current with plate voltage in Fig. 139 may be used for computing the plate current, the voltage across the tube, and the voltage amplification of a UX-240 tube under various conditions of operation. The voltage amplification per stage with a plate-supply voltage of 180 volts and a plate resistance unit of 0.3 megohms is determined with the aid of a "load line;" as, for example, the line *AB* which is drawn at the bottom of the 180-volt ordinate parallel to the reference line for a plate resistance unit of 0.3 megohm. The tube has a range of operation along the

line AB as the grid voltage is varied from zero to the point of cut-off which occurs at $E = -6$ volts. A value of grid bias should be chosen near the middle of this range in order that the "swing" of the grid towards the $E_c = 0$ line may be approximately equal to its "swing" toward the point of cut-off. In this case the proper grid bias is -3 volts, and the "*point of operation*" is at C. If now an alternating voltage having a maximum value of 1 volt is impressed on the grid circuit, the grid will "swing" from the line corresponding to $E_c = -2$ volts to the one for $E_c = -4$ volts.

MAXIMUM UNDISTORTED OUTPUT

Type	Plate voltage	Grid voltage	Amplification factor	Plate current, milliamperes	Maximum alternating input voltage, effective volts	Best load resistance, ohms	Maximum, undistorted power output, watts
UX-199	90	− 4.5	6.5	2.5	3.18	15,250	0.007
UX-199	90	− 7.5	6.45	1.3	5.30	32,000	0.014
UX-201A	90	− 4.5	8.5	2.0	3.18	15,000	0.014
UX-201A	90	− 6.0	8.4	1.2	4.24	30,000	0.017
UX-201A	135	− 9.0	8.4	2.55	6.36	22,000	0.055
UX-226	135	−12.0	8.2	3.0	8.48	20,000	0.060
UX-226	180	−16.5	8.2	3.8	11.58	20,000	0.160
UX-227	135	− 9.0	8.2	5.0	6.36	20,000	0.055
UX-227	180	−13.5	8.2	6.0	9.54	18,000	0.140
UX-120	135	−22.5	3.3	7.0	15.9	6,660	0.105
UX-112A	90	− 4.5	8.0	5.2	3.18	5,700	0.029
UX-112A	135	− 9	8.0	7.2	6.36	7,000	0.137
UX-112A	157.5	−10.5	8.0	9.3	7.42	9,000	0.181
UX-112A	180.0	−13.5	8.0	9.0	9.54	8,800	0.308
UX-171A	90	−16.5	3.0	11.0	11.58	4,000	0.105
UX-171A	135	−27.0	2.9	16.0	19.10	4,000	0.320
UX-171A	180	−40.5	2.9	20.0	28.60	4,000	0.710
UX-210	135	− 9.0	7.5	5.0	6.36	15,000	0.064
UX-210	250	−18.0	7.5	11.5	12.72	11,000	0.340
UX-210	400	−35.0	7.5	16.0	24.80	11,000	1.340
UX-250	250	−45.0	3.8	28.0	.....	4,200	0.900
UX-250	350	−63.0	3.8	45.0	.....	3,800	2.350
UX-250	400	−70.0	3.8	55.0	.....	3,600	3.250

NOTE: The values given in this table are based on three assumptions, (1) no current is permitted to flow to the grid, (2) the impedance of the load is adjusted for the best value to suit the tube, (3) a distortion of not more than 5 per cent is introduced by the effect of the second harmonic.

The "load line" intersects the grid-bias line for $E_c = -4$ volts at the point where $E_p = 147$ volts, and the line for $E_c = -2$ volts at 108 volts. The voltage amplification A may then be found from the relation,

$$A = \frac{147 - 108}{4 - 2} = 19.5 \text{ per stage.}$$

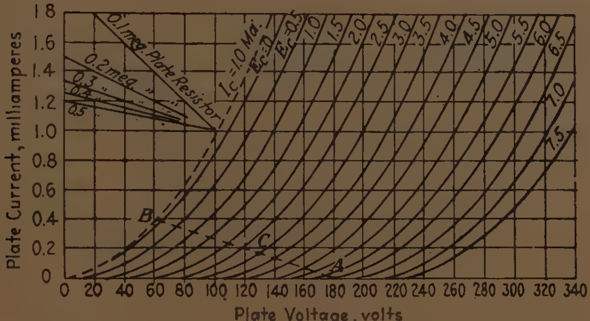


FIG. 139.—Curves for calculating plate current, voltage across tube, and voltage amplification for UX-240 tube.

The voltage across the tube is 130 volts and the plate current taken by the tube is 0.165 milliampere. Figure 140 shows the curves of voltage amplification and direct-current voltage

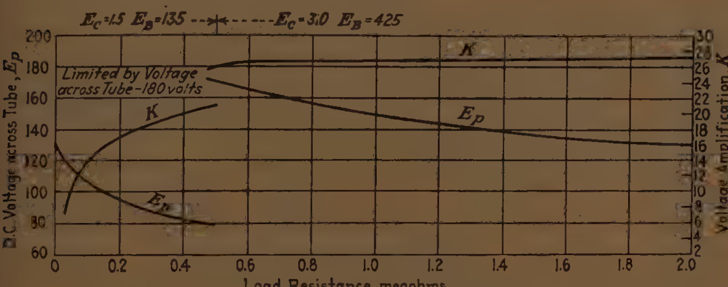


FIG. 140.—Curves of calculated voltage amplification and voltage across UX-240 tube.

across the tube which have been calculated in this way. One set of curves is for a plate-supply voltage of 135 volts and the other for 425 volts. The plate resistance unit used with such high voltages must have a sufficiently large value to

limit the voltage on the tube to 180 volts. The advantages of using such high voltages are that the amplification per stage is increased and that the distortion caused by the second harmonic is decreased.

Test for Distortion.—When a distorting component is present in a fluctuating plate current, it may be detected by the indication of a direct-current ammeter which is connected into the plate circuit as the input voltage is varied. If there is not enough external series resistance in the plate circuit to minimize this distortion, the ammeter will show an increase in reading as the input voltage increases, as, for example, on a loud radio signal. As the amount of resistance is increased, the change in the reading of the ammeter becomes less and less on loud signals showing that essentially distortionless amplification is being obtained.

Loud Speaker as a Load.—In a radio receiving set for the reception of broadcasting, the usual load on the last amplification tube is a loud speaker, which requires a relatively large amount of power in order that it may produce a satisfactory volume of sound. The direct-current resistance of the coils of the average loud speaker is about 1,000 ohms; but the impedance of a loud speaker, that is, its resistance to the varying plate current of the output tube, is much higher. This value of impedance of a loud speaker may vary from 1,000 ohms at zero frequency to 30,000 or 40,000 ohms at 5,000 cycles per second. The average impedance of a loud speaker, such as the Western Electric, is about 4,000 ohms. As improvements have been made in the range of frequencies over which the loud speaker responds, the sensitivity of the device has been reduced, with the result that an increase in power is necessary. Hence, the necessity for a determination of the power available and the distortion introduced under various load conditions. With such information, the type of tube and loud speaker may be chosen for best results.

Although the calculations in the previous paragraphs were carried out with a resistance load to simplify the solutions, they may be applied directly with sufficient accuracy for practical design work. The results which have been computed

for a range of resistance loads may be used for the corresponding impedance range of the loud speaker over the useful band of audio frequencies.

A tube having a maximum undistorted power output of at least 0.1 watt should be used with a speaker of average sensitivity for home reception. A lower power output will cause appreciable distortion. An available power output up to 0.5 watt is very desirable, if the required "B"-battery power can be supplied conveniently. With such additional reserve power the quality of reproduction is not affected if the volume is increased, or if the sensitivity of the loud speaker is poor, or if the "B" voltage is less than the rated value, as in the case of run-down dry batteries.

Tubes with low plate resistances give the best quality of reproduction, unless the output transformer is made with a step-down ratio. This construction, however, is not practical unless ample power output is available, as with the UX-210 tube when it is operated at a high voltage. The UX-171A tube gives the best quality of reproduction with the usual loud speakers because its plate resistance is less than that of any other tube operating at voltages under 200 volts. The plate resistance varies but little over a wide range of "B" voltage and, therefore, the quality of reproduction is not affected much by plate and grid voltage changes, provided the tube is not overloaded by setting the volume control of the receiving set so high that the input voltage becomes excessive.

Choice of Power Tubes.—The factors which should be considered in the selection of a power tube are, (1) the input voltage at the detector, (2) the required amount of power output, and (3) the available supply of power.

The solution of this problem is simplified by the use of the curves[1] in Fig. 141 showing the relation between the power output and *peak* grid voltage for a number of tubes for amplification. It is assumed that a peak voltage equal to the grid-bias voltage may be used, and that the amplification per stage is equal to $0.9 \times u \times$ transformer ratio. Further, it is

[1] Courtesy of General Radio Company.

assumed that the voltage in the plate circuit of the detector is equal to 0.3 volts.

The curves show that for a power output greater than 10 milliwatts, the input voltage must be in excess of 3 volts; that is, when considerable power is desired, the power tube cannot be operated directly from the detector. For input voltages up to 10 volts the UX-112A tube is better than the others.

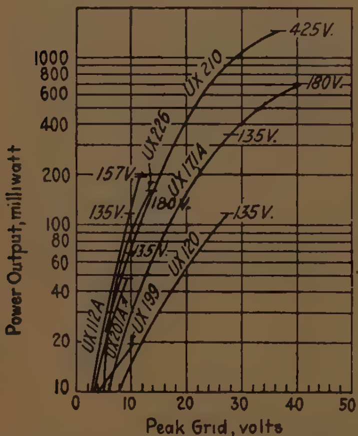


FIG. 141.—Curve showing relation between power output and peak grid voltage for amplification.

The use of the curves may be illustrated by several examples. The following method will show how a "power stage" is added to a one-stage audio-frequency amplifier which has a UX-201A tube and a transformer with a ratio of 1:2.7, when there is no restriction on the power supply. Under these conditions, the signal voltage available at the primary of a second transformer is $0.3 \times 2.7 \times 0.9 \times 8 = 5.8$ volts. If this second transformer has also a ratio of 1:2.7, the voltage at the grid of the power tube is $5.8 \times 2.7 = 12$ volts. A UX-112A tube would be overloaded by this voltage. At such a low input voltage, however, other tubes would not provide a greater output than could be obtained by operating the UX-112A tube at a slightly reduced input voltage to avoid overloading. If, on the other hand, the second transformer has a ratio of 1:5.95 the input voltage becomes $5.8 \times 5.95 = 35$ volts, which is suitable for a UX-210 tube. If, however, the plate-supply voltage had been limited, a UX-171A tube or two of these tubes in parallel would be used.

Again, a power tube may be selected for a battery-operated receiving set using 3-volt tubes with an available plate supply of 135 volts, the receiver having a transformer with a ratio of 1:2.7 in the first stage, and another transformer with a 1:6

ratio in the second stage. In this case, the voltage at the grid of the power tube is $0.3 \times 2.7 \times 0.9 \times 6 \times 6 = 26$ volts. Here, the battery requirement limits the selection to a UX-210 tube which would be overloaded by a grid input of 26 volts. It is necessary to use either a reduced voltage input, therefore, or a low-ratio transformer in the second stage. If it is possible to have a separate power stage, with alternating current supply for the power-tube filament and no restrictions on plate voltage, a UX-210 tube could be used. High plate voltage could be avoided by a parallel or push-pull connection.

The last example illustrates the design of a complete amplifier using a UX-210 power tube. The curve for the UX-210 tube shows that a voltage input of 35 volts is necessary. Then, the required gain, that is, the ratio of the voltage in the grid circuit of the power tube to the voltage in the plate circuit of the detector tube is $35 \div 0.3 = 117$. A combination of a transformer with a 1:2.7 ratio, a UX-201A tube, and another transformer also with a 1:2.7 ratio gives a gain of 53 which would not be sufficient. A transformer with a 1:2.7 ratio combined with a UX-201A tube and a second transformer with a 1:6 ratio gives a gain of 118 which is just sufficient, but is undesirable because no factor of safety is provided. A stage of impedance coupling does not give as much voltage amplification as a stage of transformer coupling. A combination of a double-impedance coupling and a UX-201A tube in the first stage, a double-impedance coupling and a UX-201A tube in the second stage, and a double-impedance coupling in the third stage gives a gain of about 49 which would not be sufficient. A similar combination with the last impedance replaced by a transformer with a 1:2.7 ratio gives a gain of 147 volts. An even better arrangement is obtained if a transformer with a 1:6 ratio is substituted for the impedance coupling in the combination just described, so that a gain of 330 is obtained, this voltage being high enough to permit the operation of the detector tube with a lower signal voltage than in the other cases.

CHAPTER IX

USE OF VACUUM TUBES AS OSCILLATION GENERATORS

Explanation of Action as an Oscillator.—The three-element vacuum tube, connected in a suitable circuit, may be used as an oscillator to establish and maintain an alternating current of constant frequency. The constants of the circuits may be designed to cover a frequency range of from one cycle per second to several hundred million per second. The usual detector or amplifier tube may be used as an oscillator but for large outputs of power an *oscillator tube* is necessary.

The operation of simple continuous-wave radio-transmitting sets as well as that of heterodyne receiving sets depends upon this action. In laboratory and industrial work the vacuum tube oscillator finds application as a source of pure alternating current of constant amplitude. The production of such an alternating current depends upon the control which the grid voltage exerts on the plate current; that is, a small amount of energy applied to the grid controls a large output from the plate battery. Several mechanical illustrations of this action may be given. Thus, a steam hammer is controlled by applying a very small force to the steam valve through an operating handle. The steam valve allows the boiler pressure to act. The action may be made automatic by an arrangement which moves the valve when the hammer reaches the end of its stroke. Here, a portion of the power in the controlled circuit is put back into the controlling circuit to maintain the action. In the case of the vacuum tube, the grid corresponds to the steam valve and the plate battery voltage corresponds to the steam pressure.

Another mechanical illustration is that of the action of a clock. As the pendulum swings it works the escapement

which permits the main spring to deliver a push to the pendulum during each swing in such a direction as to increase the extent or amplitude of the swing. When the friction of oscillation becomes equal to the impulse given by the spring, the amplitude of oscillation will stop increasing and remain constant. In the case of the vacuum tube, the grid corresponds to the clock escapement, the plate battery corresponds to the main spring, and the current in the oscillating circuit, which is connected to the plate of the tube, corresponds to the pendulum. The current in the oscillating circuit reacts on the grid so as to change the value of the voltage across the grid circuit. This change in grid voltage produces a change in the plate battery current, which, in turn, acts upon the oscillating circuit so as to increase the oscillating current. This action continues until a balance is reached between the losses due to radiation and heat, and the power supplied by the tube. Beyond this point, the amplitude of the oscillating current remains constant in value.

Simple Oscillator.—If a certain portion of every oscillation produced in the plate circuit is put back into the grid circuit in the correct time relation, the pulsating-current wave generated in the plate circuit will be continuous.

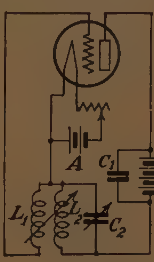


FIG. 142.—Simple oscillator for producing alternating current.

A simple arrangement for producing an alternating current by the use of a vacuum tube is shown in Fig. 142. The inducance L_2 and the condenser C_2 have values such that their natural period of vibration corresponds to the desired frequency. The inductance, or the capacity, or both, may be variable if it is desired to change the frequency of the current. The inductance coil L_1 which is coupled to L_2 receives some energy from the oscillating circuit L_2C_2. The coupling coils L_1 and L_2 must be connected in such a manner that the oscillations in the grid circuit assist those in the plate circuit. The degree of coupling must be such that the small amount of energy transferred to the grid circuit will, when amplified, maintain the variations of current and cause the

plate oscillations to be continuous. The first electrical disturbance in the oscillating circuit might be caused by a movement of electrons in the tube as a result of a change in the capacity of the circuit, or because of the flow of a small current when the "A" or the "B" battery circuit is closed. These weak oscillations in the oscillating circuit will induce an alternating voltage in coil L_1 which acts upon the grid and produces variations in the plate current flowing through the oscillating circuit. If the coupling between the coils is correct, the original oscillations are reinforced. Although the amplitude of the current during the first cycle may be small, the additive effect of the feed-back action increases the amplitude of each successive wave. This increase continues until the energy generated is just sufficient to maintain a current of a certain strength. Beyond this point a pure unvarying wave of alternating current is produced in coil L_1 or any other coil in a circuit coupled to the plate circuit. Usually, the constant state is reached in a very small part of a second after operation of the tube is started. The frequency of the alternating current then flowing in the circuit is very nearly that of the natural period of the oscillating circuit. The operation of the tube is quite like that of a regenerative amplifier because the tube actually amplifies the small amount of energy transferred from the plate circuit to the grid circuit.

A current in the plate circuit sets up, in the L_2C_2 circuit, a voltage which is 90 degrees out of phase with the plate current, provided that the resistance of the L_2C_2 circuit is very small. The oscillating current in the L_2C_2 circuit is in phase with the voltage in this circuit because the L_2C_2 circuit is considered to be non-reactive at the frequency of oscillation. The oscillating current induces in the grid coil L_1 a voltage which is 90 degrees out of phase with that current. That is, the plate circuit reacts upon the grid circuit in such a way that the induced grid voltage is in phase with the plate current.

Detection of Oscillating Condition.—The most accurate and absolute test to determine when a tube is oscillating is to use a sensitive radio ammeter in the oscillating circuit. The meter will show a reading when the oscillating current is established.

Typical Oscillator Circuits.—There is a great variety of circuits in which the plate circuit is coupled back to the grid circuit in such a manner as to supply a small amount of power to the grid and make the surplus available for use in an external circuit in the form of continuous oscillations.

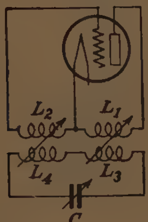


FIG. 143.—Meissner oscillating circuit.

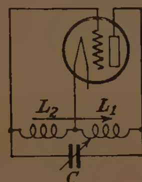


FIG. 144.—Hartley oscillating circuit.

This feed-back action can be obtained by the use of (1) direct coupling from the plate back to the grid circuit, (2) by inductive coupling, or (3) by electrostatic coupling. The main requirement for continuous oscillations is that the voltage induced in the grid circuit must produce variations in the amplitude of the plate current which are sufficient to maintain the voltage in the grid circuit.

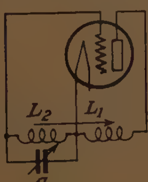


FIG. 145.—Tuned grid oscillating circuit.

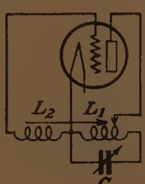


FIG. 146.—Tuned plate oscillating circuit.

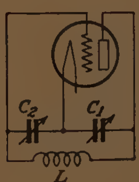


FIG. 147.—Colpitts oscillating circuit.

A number of the usual arrangements are shown in Figs. 143 to 147. In Fig. 144 L_1 and L_2 may be coupled together if desired, and in Fig. 145 such coupling is usually necessary in order that the voltage applied from the plate circuit may maintain the oscillations. In Fig. 146 the coupling is necessary in order to obtain the control of the grid voltage because

L_2 is not in the oscillating circuit. A reversal of the coil connections in these circuits (except the "Colpitts," Fig. 147) usually will change the phase relations.

Conception of Negative Resistance.—In an ordinary oscillating circuit, the circuit resistance in ohms is proportional to the rate of energy consumption in the circuit. In an oscillating circuit used with a vacuum tube as described above, the tube through its operation feeds back energy to the circuit. The rate of such feed-back may be considered as a *negative* resistance which tends to neutralize the ohmic resistance of the oscillating circuit. If this negative resistance is less than the ohmic resistance of the oscillating circuit, the oscillations are damped. The extent of this damping, however, is less than if no negative resistance was introduced. If the negative resistance is equal to the ohmic resistance, the oscillations are maintained indefinitely once the process is started. If the negative resistance is greater than the ohmic resistance, the circuit will start oscillating of itself. The amplitude of oscillations will increase until the capacity of the circuit to supply energy is reached.

Requirements for Oscillations.—Some of the general conditions for oscillation have been stated. In order to examine the requirements more in detail, it is necessary to consider the character of the plate current and the influence of the constants of the circuit.

The varying plate current may be taken to consist of two parts, a direct current and an alternating current. It is this alternating current in the oscillating circuit which gives rise to the voltage acting on the grid and maintaining the oscillations. In order to bring this about, the alternating plate current and the grid voltage must be in phase. That is, when the alternating plate current reaches its maximum positive value, for example, the total value of plate current is high and the oscillating current must act through the grid coupling in such a manner that the grid voltage is at a positive maximum. If the voltage applied to the grid produces, by means of feedback, an equal or greater voltage on the grid, the tube will oscillate.

A determination of the effect of the circuit and tube constants upon the requirements for oscillation may be made in a simple manner. A circuit such as that of Fig. 4 may be used with the assumption that the oscillations are small in value, that the impedance of L_1 is small compared to the tube resistance r_p, and that the characteristic curve is a straight line. The alternating plate current then is

$$I_p = \frac{uE_g}{r_p}$$

where E_g is the alternating voltage applied to the grid. The voltage induced in the grid circuit by means of the mutual inductance M depends upon this plate current I_p and is equal to I_pwM or, by substitution, $uE_gwM \div r_p$. This voltage causes a current to flow through the resistance R of the tuned-grid circuit equal to uE_gwM/Rr_p. This feed-back current multiplied by wL_2 or by $1/wC$ gives the value of the voltage E_g' impressed on the grid through the feed-back action. That is, $E_g' = uE_gM/Rr_pC$. The tube will oscillate if E_g' is equal to or greater than E_g. Since

$$\frac{E_g'}{E_g} = \frac{uM}{Rr_p}$$

the condition for oscillation is given by the statement that uM/Rr_pC must be equal to or greater than 1. That is, the tendency for the generation of oscillations is increased by increasing u or M or decreasing R or r_p or C.

The circuit shown in Fig. 146 requires a somewhat different expression for the oscillation requirements. In this case, the oscillating circuit L_1C has a resistance R. In a freely oscillating circuit like L_1C, when not connected to a tube, the resistance R determines the action. It may be shown that the oscillating circuit L_1C of Fig. 146, however, behaves as if its resistance were $R + \dfrac{L_1 + uM}{Cr_p}$. That is, the oscillating circuit resistance is increased by an amount $\dfrac{L_1 + uM}{Cr_p}$. The quantities L_1, C, u and r_p are positive but M may be either positive

or negative, depending upon the coupling connections between the coils. If M is positive, the equivalent resistance of the oscillating circuit is increased and the damping of oscillations is more rapid than would be the case in a freely oscillating circuit. If M is negative, the equivalent resistance is decreased and may be made equal to zero or even negative. In order that the quantity $\frac{L_1 + uM}{Cr_p}$ may be equal to $-R$, the term M must be equal to or greater than $-\frac{Cr_p}{u}\left(R + \frac{L_1}{Cr_p}\right)$. If the equivalent resistance is negative, the amplitude of the oscillations increases up to the energy limits of the tube. Beyond this point the amplitude is constant and the current has a frequency of $f = \frac{1}{2\pi}\sqrt{\frac{R + r_p}{r_p L_1 C}}$. As the term R/r_p generally is small, the frequency is very nearly equal to the natural frequency of oscillation of a freely oscillating circuit L_1C, which is given by $f = \frac{1}{2\pi}\sqrt{\frac{1}{L_1C}}$.

Frequency of Oscillation.—When the grid circuit is connected to an outside source of power the tube will reproduce in the plate circuit the frequency which has been impressed on the grid circuit. But when the tube is self-excited by coupling the grid and plate circuits together, the frequency on the grid is the same as that which is produced in the plate circuit. The frequency of operation then is determined by the electrical constants of the circuit and corresponds to the natural frequency of a mechanically vibrating body. This critical frequency is known as the *resonant* or *natural frequency*.

The frequency of oscillation of the circuit shown in Fig. 144 is

$$f = \frac{300{,}000{,}000}{1{,}884\sqrt{(L_1 + L_2)C}}$$

where f is the frequency in cycles per second, L_1 and L_2 are the inductances of the coils in microhenrys and C the capacity of the condenser in microfarads. If there is any magnetic

coupling between the coils and if M is the mutual inductance of the two coils the expression for frequency becomes

$$f = \frac{300,000,000}{1,884\sqrt{(L_1 + L_2 + 2M)C}}.$$

Frequency Control with Piezo-electric Crystal.—The vacuum tube transmitter used in broadcasting must generate a constant frequency. Accurate maintenance of frequency is possible by the use of a piezo-electric crystal control if the temperature of the crystal is kept constant.

Certain crystals such as quartz possess the property of developing an electric charge when they are put under pressure, and *vice versa;* that is, they change in shape under the action of an electrostatic field. Consequently, the frequency of oscillation of a vacuum tube may be controlled by the mechanical vibration of a quartz crystal.

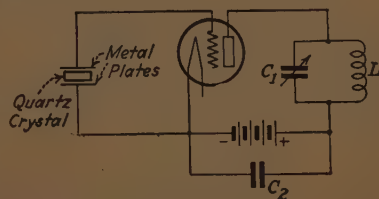


FIG. 148.—Device for frequency control with quartz crystal.

This effect is obtained by an arrangement such as that of Fig. 148. The condenser consisting of a small disc of quartz between two metal plates is placed in the grid circuit of a vacuum tube. If an alternating potential difference is established between the two plates of the condenser, the crystal will vibrate mechanically at its natural period. When the plate circuit is tuned electrically to the same frequency as that of the crystal, the circuit will oscillate and variation of the capacity C_1 does not affect the frequency of oscillation. A small *master oscillator* of this kind is used to excite a large power tube and thus controls the frequency accurately.

Variation of Oscillation with Coupling.—As the coupling between the coils of the circuits in Figs. 143 to 147 is made looser, a greater alternating current in the coil L_1 is required for a given alternating grid voltage induced in coil L_2. Thus, as coupling is reduced, the oscillation increases until the plate current varies between the saturation value and approxi-

mately zero, as shown in Fig. 149. When the condition of stable oscillation has been reached, the oscillating current has a value of $\frac{I_s}{2w}\left(CR + \frac{L_1}{r_p}\right)$ where I_s is the saturation current. Since the plate current cannot increase beyond this upper value, an additional reduction of coupling will decrease the induced grid voltage until the action stops.

A different result is obtained as the coupling is increased. Under this condition, the oscillations decrease and stop when the coupling is too tight. The best value of coupling, then, for allowing oscillation to be greatest, is seen to lie between the upper and lower limits, at each of which the oscillations reduce to zero.

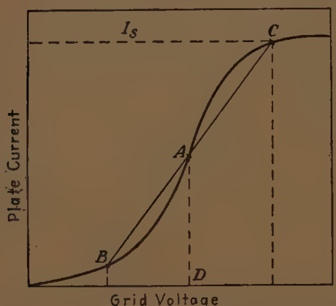


FIG. 149.—Curve showing variation of oscillation with grid voltage.

When the coupling between tuned circuits is close, oscillations of two different frequencies may take place. When the direct-coupled circuits are used, harmonics are found in the antenna current. Consequently, it is advantageous to sacrifice efficiency, when coupled circuits are used, so that the interference may be decreased.

In some cases, the presence of another oscillation frequency is caused by the distributed capacity of coils, the inductance of the wiring, and the tube interelectrode capacities. This difficulty is minimized in a capacity-coupled circuit as in Fig. 147, because the capacities of the tube electrodes and of the wiring are in parallel with the circuit condensers. Similarly, the circuit arrangement in Fig. 144, in which the internal grid-plate capacity of the tube is in parallel with the capacity C of the oscillating circuit, is suitable for use at high frequencies.

In most circuits, the coupling between the input and output circuits is adjusted by changing the mutual reactance. When a change in coupling, however, depends upon a change in capacity, as in the circuit of Fig. 147, the frequency of the oscillating circuit is affected. One way of avoiding this

difficulty is to insert, in series with the inductance, another condenser which may be used to regulate the frequency.

Variation of Oscillation with Grid Voltage.—The operating point A in Fig. 149 is taken at the center of the characteristic curve. Then, if the mutual inductance M has the value given above, the oscillations will start and the grid voltage will vary about the original value D. When the amplitude of oscillations increases until the plate current varies over the line BC, a stable condition is obtained.

Now, if the grid-bias voltage is made more negative so that operation is at the lower bend of the characteristic curve, the mutual conductance u/r_p (slope of the curve at the operating point) decreases. This may affect the conditions for oscillation to such an extent that the generation of oscillations will not take place unless the coil coupling is increased.

If a still greater negative grid-bias voltage is used, so that operation takes place on a horizontal part of the curve, the mutual conductance is zero. If the oscillating circuit is started in some way, an alternating voltage is induced in the grid circuit. Variations of this grid voltage, however, do not cause any variations of the plate current. Consequently, the oscillations die away and the tube does not operate.

In practice, however, the grid is not negative enough at all times with respect to the filament to prevent the flow of grid current. For example, when a grid condenser and grid-leak resistance are used to keep the grid negative, the grid becomes positive during a part of the cycle. If the plate becomes *less* positive as the grid becomes *more* positive, the flow of grid current increases and if, at any instant, the highest positive grid voltage approaches the value of the lowest plate voltage, the plate current is decreased considerably. Consequently, saturation seems to occur at a value of plate current which is lower than the normal value.

It should be noted that the output power increases with the square of the alternating voltage applied to the grid for small values of voltage. For large values of grid voltage, however, the output power may vary with a fractional power of the grid voltage.

Variation of Oscillation with Plate Voltage.—With a given plate voltage, only a certain portion of the filament emission can be utilized, but, with a given emission, an increase in plate voltage increases the output up to the limit of the tube.

The expression which has been given for the condition necessary to generate oscillations may be stated in another form. That is, M must be equal to or greater than $\frac{r_p}{u}\left(CR + \frac{L_1}{r_p}\right)$, or, $\frac{u}{r_p}$ must be equal to or greater than $\frac{1}{M}\left(\frac{L_1}{r_p} + CR\right)$. The term u/r_p, which is the mutual conductance of the tube, is proportional to the plate voltage. The term $\frac{1}{M}\left(\frac{L_1}{r_p} + CR\right)$ also is proportional to plate voltage. Then, since u/r_p must be at least equal to $\frac{1}{M}\left(\frac{L_1}{r_p} + CR\right)$, oscillations will not be generated if the plate voltage is below a value which is determined by the quantities L_1, C, R, r_p, and M.

Practical Arrangement of Circuits.—The location of batteries in a transmitting circuit introduces several matters which must receive consideration. A diagram of a simple "Colpitts" circuit is shown in Fig. 150. No direct current can pass through the oscillating circuit from plate to filament because of the blocking action of condensers C_1 and C_2. The choke coil L_p passes the direct current of the plate battery but blocks the high-frequency portion of the plate current which flows through the oscillating circuit and maintains the oscillations. The inductance of the choke coil is made high so that its impedance may be several times the plate resistance of the tube. The filament is insulated from the plate voltage by the fixed condenser C_g. The capacity of C_g is chosen large enough so that it does not have much effect on the operation of the oscillating circuit. An accumulation of negative charges on the grid is prevented because of the

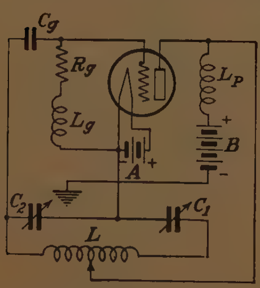


FIG. 150.—Colpitts oscillating circuit arranged for practical operation.

leakage path provided by the grid leak resistance R_g and the choke coil L_g. The antenna is represented by C_1 with the ground connection near the filament. The coupling to the grid circuit is obtained by the condenser C_2, increased capacity giving decreased coupling. Adjustment of the load is accomplished by moving the tap on the coil L.

The batteries should be grounded to the same point which is used for grounding the tube circuit. For this reason the batteries and the antenna ground usually are located near the filament. If a ground at another point is used for the batteries, another circuit due to the capacity of batteries to ground will be set up parallel to the oscillating circuit with consequent loss of power and a possible reduction of oscillations.

Circuits for the generation of currents of high frequencies of the order of several hundred million cycles per second are simplified considerably. Sufficient inductance for such circuits is provided by the inductance of the connecting wires, and the internal grid-plate capacity of the tube constitutes the necessary capacity. In fact, the interelectrode capacities of a tube determine, for the most part, the upper limit of frequency which may be obtained.

A comprehensive study of the construction and operation of transmitters designed for use in the new amateur communication bands listed for 1929 may be found in the current issues of *QST* published by The American Radio Relay League.

Conditions for Maximum Current.—The current in the oscillating circuit can be made a maximum when the load in the plate circuit is the proper one for the tube used. The load in the plate circuit of an arrangement such as that in Fig. 146, for instance, depends upon the inductance L_1, the capacity C, and the resistance of the oscillating circuit to high-frequency currents. The *load* resistance has a high value when the inductance L_1 is large or when the capacity C and the circuit resistance are small; that is, if C is a low-capacity antenna and if the radio-frequency resistance of the circuit is small, the radio-frequency resistance of the load may be above the maximum for the tube in question. Under these conditions, oscillations will be generated but the current will not be a

maximum. The load may be decreased by adjusting the tap on L_1 so that less inductance is included in the plate circuit. On the other hand, if the capacity of the antenna is high or if the radio-frequency resistance of the circuit is large, the current will be a maximum when the tap is adjusted so that more inductance is included in the plate circuit. If the filament voltage or plate voltage is changed, a readjustment of the plate inductance must be made to suit the load to the new operating conditions. Excessive grid voltage may be avoided by adjusting the control for the coupling of the inductance coils.

If the power output of a tube is plotted against the equivalent resistance of the oscillating circuit at the frequency of resonance, it will be observed that the power output is a maximum when the equivalent resistance is equal to the plate resistance of the tube. The ratio of inductance to capacity of the oscillating circuit can be determined, if the value of equivalent resistance is known. It is necessary to keep in mind the fact that a condition of maximum output power does not correspond to a condition of maximum efficiency.

Efficiency of Oscillator Tubes.—The efficiency of a vacuum tube oscillator may be expressed as the ratio of output power to input power. The power expended in heating the filament is not included; in high-power oscillator tubes this quantity is comparatively small, but in low-power tubes it may be greater than the output power. The output power, which usually defines the rating of a power tube, is the product of the square of the radio-frequency current and the radio-frequency resistance of the oscillating circuit. The input power, supplied by the plate battery, is the product of the battery voltage and the battery current. Thus, in the case of the UX-210 tube, which is rated at 7.5 watts, the plate current is 0.06 ampere at a plate voltage of 350 volts, when the tube is oscillating. The efficiency is

$$\text{Eff.} = \frac{\text{Output}}{\text{Input}} = \frac{7.5}{0.06 \times 350} = 0.357 = 36 \text{ per cent.}$$

Under the best conditions of operation, and when the grid voltage varies about a point near the center of the characteris-

tic curve, half the battery power is taken in overcoming the interval resistance of the tube, and half is taken in overcoming the resistance losses in the oscillating circuit. Under these conditions, the tube as a transformer of direct current into *pure* alternating current has a theoretical limit of efficiency of 50 per cent. A negative grid-bias voltage may be applied, however, so that the grid voltage varies about a point on the lower bend of the curve. If the plate current flows only during that part of the cycle when the alternating grid voltage is positive, the average plate current is reduced. When the plate takes current, the plate voltage is reduced because of the voltage drop through the external load. Consequently, the amount of power dissipated in the tube itself is decreased. Input power, however, as used in determining tube efficiency, consists of the power dissipated in the tube and of the power supplied to the oscillating circuit. Under these conditions of operation, then, the input power and, in turn, the efficiency, is increased. But as efficiency increases the output power decreases.

The efficiency of low-power oscillator tubes is about 20 to 35 per cent; of medium-power tubes, about 40 to 60 per cent; and of high-power tubes about 85 per cent. It is obvious, of course, that efficiency varies, also, with the adjustment of the circuit.

Suppression of Oscillations in Multi-stage Amplifiers.—In an amplifier tube circuit the internal grid-plate capacity of the tube acts as a feed-back capacity and thus permits the generation of continuous oscillations. This action increases when the frequency of the oscillations generated is high, because then the reactance of the internal grid-to-plate capacity is small. Such feed-back interferes with the proper operation of the amplifier. Oscillations, of course, may be generated, also, because of the action of stray fields upon various parts of a receiver. In many cases, such oscillations may be avoided by shielding the apparatus properly, by placing the units so that their fields do not interlink, or by connecting them so that their fields are reversed.

Several methods of suppressing or minimizing the generation of oscillations due to the internal capacity of a tube have been

mentioned in Chap. VIII. It will be of advantage to review these briefly, keeping in mind the action of the tube as an oscillator.

The first general method consists of increasing the resistance of the grid circuit, the plate circuit, or both, by inserting a resistance unit. When the resistance thus introduced is greater than the negative resistance due to the feed-back action, the generation of oscillations is suppressed.

Another method, which is similar, depends upon the application of a small positive grid-bias voltage to the grid of the tube. This allows a current to flow in the grid circuit, resulting in an energy loss to counterbalance the introduction of energy into the circuit through feed-back. The disadvantages of this general method are (1) increase of losses in the circuit, and (2) decrease in selectivity.

Another method has the effect of neutralizing the oscillations. The generation of oscillations is favored when the coupling between the grid and the plate circuits is negative; that is, when the equivalent resistance of the grid circuit is less than the resistance of the actual circuit. If, however, a coupling of the opposite kind, referred to as a *positive coupling*, is established between the grid and the plate circuits, its value may be so chosen as to neutralize the effect of the negative coupling. Several types of this method have been mentioned previously.

CHAPTER X

SPECIFICATIONS FOR VACUUM TUBES

The service for which vacuum tubes are designed may be summarized as follows: (1) detection, (2) radio-frequency amplification, (3) audio-frequency amplification, (4) power output, and (5) oscillation. The various types of tubes which are available for this service may be grouped as (1) general-purpose tubes, (2) alkali-vapor tubes, (3) tubes with high amplification factor, (4) tubes with low amplification factor, and (5) high voltage tubes.

Detection Service.—For detector service, best results are obtained with general-purpose tubes, alkali-vapor tubes, and tubes with high amplification factors. The general-purpose tubes include the UX-201A, UX-199, WD-11, and WX-12. The UX-226 tube is a general-purpose amplifier, and UY-227 is a detector and amplifier. Intermediate between the general-purpose and the power-amplifier tubes is the UX-112A type.

The moderately high sensitivity and low plate resistance of general-purpose tubes make them well suited for detection. They will take a fairly strong input voltage before becoming overloaded and may be used for either grid-leak or grid-bias detection. The alkali-vapor detector tube UX-200A has far greater sensitivity as a detector than other types.

The UX-240 tube is a high amplification type and is intermediate between the general-purpose and the alkali-vapor tubes with respect to sensitivity. It should be used as a detector with resistance- and impedance-coupled audio amplifiers.

Radio-frequency Amplification.—The general-purpose tubes are well suited for use in radio-frequency amplifiers. The selectivity and sensitivity of the amplifier depends upon the

proper turn ratio of the number of turns of the windings in the tuned-output circuit. The value of interelectrode capacity is moderate and may be neutralized by certain circuit arrangements. The UX-226 tube is intended for radio-frequency amplification in receivers operated with alternating current.

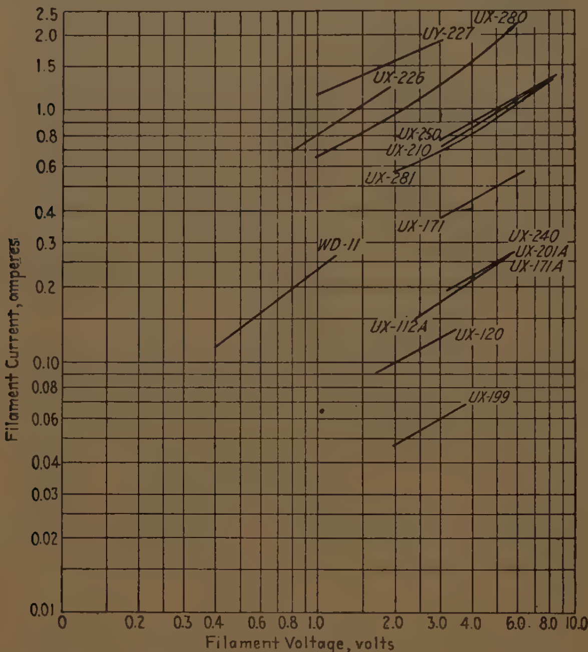


FIG. 151.—Relation of filament current to filament voltage of typical vacuum tubes.

In many cases, the UX-112A tube gives excellent results on radio-frequency amplification. When used for such work, it should be provided with a sufficient negative grid-bias voltage to avoid an unnecessarily high value of plate current.

Audio-frequency Amplification.—The general-purpose tubes may be used in audio-frequency amplifiers. Most audio transformers have been designed for operation with these tubes which have the advantages that they require low plate current and a low plate resistance. The UX-240 tube which

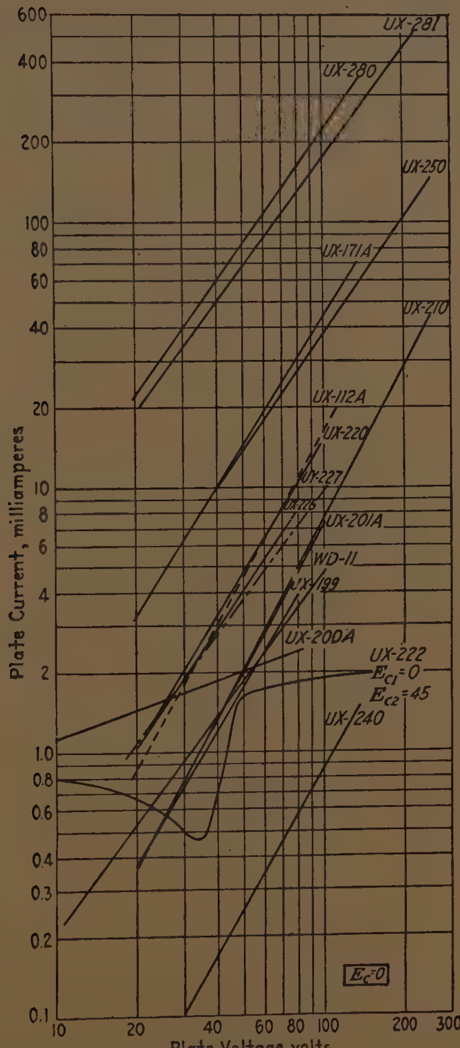


FIG. 152.—Relation of plate current to plate voltage of typical vacuum tubes.

has a high amplification factor may be used in an audio-frequency amplifier as described on page 231.

Power Amplifier Tubes.—When the plate current requirements can be met, UX-171A tube of the low amplification-factor type is preferred for use as a power amplifier. It

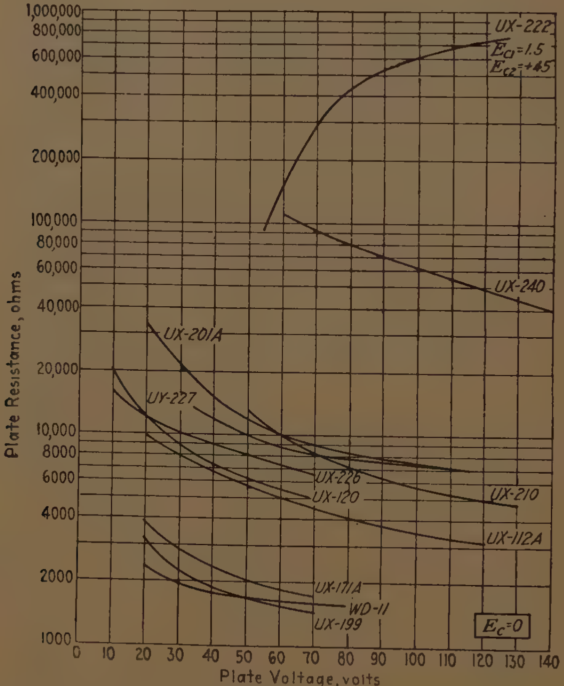


FIG. 153.—Relation of plate resistance to plate voltage of typical vacuum tubes.

offers the advantage of ample undistorted power output at moderate plate voltages. On the other hand, when high plate voltages are available, as in power amplifier equipment, the use of a UX-210 tube provides a large reserve of available power and thus insures maximum tone quality.

Oscillation Service.—Tubes operating as oscillators in radio receiving sets, such as the superheterodyne types, require

very little power. For such work any of the general-purpose tubes are satisfactory.

Specifications.—Detailed specifications of various vacuum tubes are given in the following paragraphs. Comparative characteristic curves of these tubes are given in Figs. 151, 152, 153, 154, and 155. The corresponding numerical values for various conditions of operation are listed in the tables on pages 108 and 109.

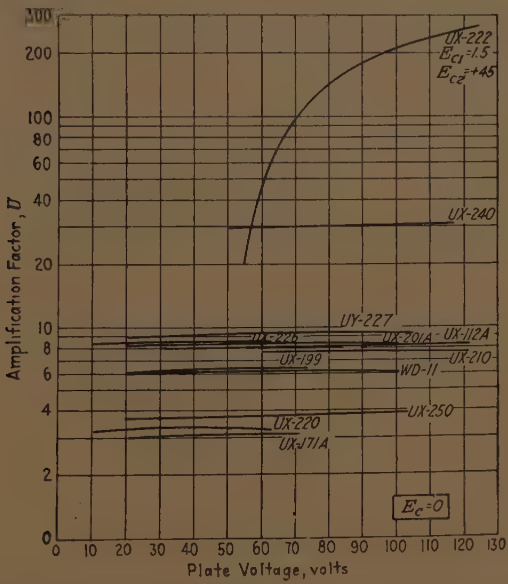


FIG. 154.—Relation of amplification factor to plate voltage of typical vacuum tubes.

Dry-cell Vacuum Tubes. Types WD-11 and WX-12.—There are several types of vacuum tubes which are designed primarily for detection and audio-frequency amplification in radio receivers operated by dry batteries. The WD-11 and WX-12 types of tubes are intended for a filament voltage of 1.1 volts, permitting the filament to be energized by a single No. 6 dry cell, a particular advantage in one- to three-tube portable sets. The WD-11 tube has a push-type base designed to prevent insertion into a standard socket connected into a

circuit having a 6-volt supply. The WX-12 tube fits the "UX" type of socket. The filament of each of these tubes is coated with an oxide and is rated at 0.25 ampere at 1.1 volts. The filament should be burned at a cherry red heat, *not* brightly. Excessive temperature tends to drive off the oxide coating. The filaments of these tubes *cannot be reactivated* (see page 79). Any attempt to do so burns out the filament.

Operation as a Detector.—The standard detector circuit with grid leak and condenser is used with the WD-11 and UX-12 tubes, the grid being connected to the positive side of the

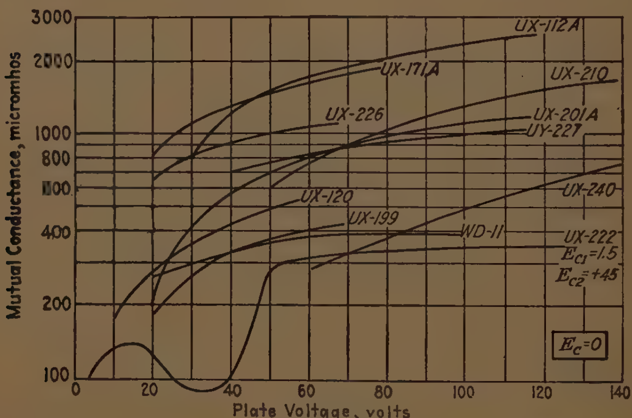


FIG. 155.—Relation of mutual conductance to plate voltage for typical vacuum tubes.

filament. A grid leak of 2 megohms and a condenser of 0.00025 micro-farad are recommended. The normal plate voltage is 22.5 volts, but 45 volts increases signal strength slightly. In regenerative sets, the tube operates smoothly. A nominal amount of cushioning suffices to prevent noises. Any standard cushion socket is satisfactory.

Operation as Audio-frequency Amplifier.—The plate impedance of the WD-11 and WX-12 tubes is suitable for audio-frequency amplification with standard transformers. The use of a negative grid potential from a "C" battery is not absolutely necessary on small amounts of power. When

greater power output is required, the following negative grid voltage should be used:

Plate Voltage	Negative Grid, "C" Battery, Volts
40–45	0.5 to 1.5
60–70	3.0
80–90	4.5

The plate voltage limit is 100 volts. Voltages in excess of 67.5 volts should not be used without a "C" battery. Without a "C" battery to limit the flow of plate current, this current requirement may be in excess of the available filament emission, resulting in increased plate impedance, distortion, and limitation of power output.

Operation as Radio-frequency Amplifier.—The interelectrode capacity of each of these tubes is moderately high and they are not, therefore, especially adapted for radio-frequency service in "un-neutralized" receivers.

Dry-cell Vacuum Tubes, Type UX-199.—For general-purpose services the UX-199 tube is designed for detection, radio amplification, and audio amplification. It has a filament which is suitable for operation with dry cells. The UX-199 tube is mounted on the (small) standard UX base, and a similar tube known as type UV-199 is mounted on a small navy-type "bayonet" base.

The filament of the UX-199 tube is of thoriated tungsten requiring 63 milliamperes at 3.3 volts and can be operated from three No. 6 dry cells in series. In portable sets, where weight and space are factors, smaller dry cells may be used but with a higher operating cost. Two-cell storage batteries may be used for filament supply with multi-tube sets.

The filament should be operated at constant voltage, as an overload voltage causes a loss of emission and shortened life. A filament voltmeter is recommended especially in multi-tube sets, where one faulty tube may cause excessive filament voltage on all the tubes. High-resistance voltmeters of good accuracy should be used. The voltmeter should be connected across the filament during operation unless the meter requires

less than 15 milliamperes. Otherwise, the removal of the meter changes the current through the rheostat sufficiently to increase the terminal voltage.

So-called "automatic" non-adjustable filament controls are not satisfactory with this tube because of the low filament current. When they are used, the tube is subjected to overload voltage with fresh dry cells. Also, the cells must be discarded before completely exhausted.

It is advisable to use the rheostat as a switch to open the filament circuit. The maximum resistance is then in circuit for restarting. One reason for this is that near the end of the normal life of dry cells the initial voltage, after a period of rest, is considerably above the normal voltage during the discharge period.

Operation as Detector.—For the operation of the UX-199 tube as a detector, the grid-return lead is connected to the positive side of the filament. A 3-megohm grid leak and 0.00025-microfarad condenser are recommended. Higher grid-leak resistance may be used on weak reception with an increase in sensitivity. A plate voltage of 45 volts is recommended for detector operation. In regenerative receivers, this tube operates smoothly with the usual values of feed-back. A cushioned socket is required when this tube is used as a detector.

Operation as Audio-frequency Amplifier.—The plate impedance is low enough to insure satisfactory quality of reception with standard audio-frequency transformers. In portable receivers it is advisable to operate the audio amplifiers at 45 volts of plate voltage for "B" battery economy. In this case sufficient grid-bias voltage is obtained by using the drop across a rheostat in the negative lead of the filament circuit.

The tube can furnish sufficient power output as an amplifier to operate small loud speakers. Voltages higher than 90 should not be used. This type of tube should not be operated above 67.5 volts of plate voltage without the "C" voltage recommended in the table on page 108. Without this "C" battery even a small decrease in electron emission reduces the efficiency.

Operation as Radio-frequency Amplifier.—This tube will give satisfactory operation in radio-frequency amplifiers and in the intermediate stages of superheterodyne receivers because of its low interelectrode capacity and high mutual inductance. Not more than 67.5 volts should be used on the plate without a "C" battery.

It is preferable to mount the tube vertically with a cushion type of base, to prevent noises. In most cases, it is sufficient to cushion only the detector tube. Frequently, the advantages of a cushioned socket are lost by the use of stiff wire connections. Flexible wire should be used.

Dry-cell Power-amplifier Tube, Type UX-120.—Type UX-120 vacuum tubes are designed for dry-cell operation as power amplifiers for loud speakers with UX-199 tubes. The UX-120 tube is used only in the last audio stage of a receiving set. The undistorted output of this amplifier tube is greater than that of two UX-199 tubes in parallel and about double the undistorted output of a UX-201A tube. The filament may be reactivated (see page 79) by use of the voltages specified for UX-199 tubes.

Operation as Power Amplifier for Loud Speaker.—The characteristics of this tube are such that it requires a high input voltage. A UX-120 tube will handle without distortion four times the input voltage which can be supplied to UX-199 tubes. For low input voltages, however, less volume is obtained from the UX-120 tube than from the UX-199 tube. This tube has a low amplification factor. As a result a high "C" battery voltage for negative grid biasing is required. Hence, under ordinary operating conditions the grid will not become positive and distortion from the flow of grid current is avoided. Maximum output power is obtained at a plate voltage of 135 volts. The plate voltage may drop to 120 volts before the output is affected.

Screen-grid Amplifier Vacuum Tube, Type UX-222.—The characteristics and performance of UX-222 tubes are made possible by the insertion of a second grid, between the usual grid and the plate, which is carried over outside the plate.

Thus, the plate is completely shielded or screened from the control grid by the second grid.

If the plate is disconnected from the source of its voltage supply, and the screen grid used as the plate electrode, the tube operates as the usual three-element tube. In operation as a four-element tube, 45 volts are applied to the screen grid, and a higher voltage (90 to 135 volts) to the plate. The usual grid terminal is connected to the screen grid and not to the control grid as is the case of three-element tubes. The filament provided in the UX-222 is similar to that in the UX-120 tube. The connection to the control grid is brought out at the top of the bulb. Because the screen grid is between the plate and the control grid, and completely surrounds the plate, it eliminates almost completely all electrostatic capacity between the control grid and the plate.

Use as a Radio-frequency Amplifier.—This four-element tube is designed for use as a radio-frequency amplifier. The advantage gained by its use is the elimination of all feed-back through capacity coupling between the grid and the plate. It is possible to obtain higher voltage amplification per stage, 25 to 50 in the broadcast range as compared with the usual range of 5 to 12 with three-element tubes.

In the operating range, the plate current does not vary appreciably with plate voltage changes due to the screening effect of the second (screen) grid. As a result, the amplitude of the plate-current change, which is caused by a voltage impressed on the grid, is scarcely affected by an increase in load resistance. Thus, it is of advantage to use a very high resistance or impedance in the plate circuit, to obtain high-voltage amplification.

At low radio frequencies, 50 to 100 kilocycles, it is possible to get a voltage amplification of 200 per stage. At broadcast frequencies the resonant impedance is lower, reducing the amplification to about 50 per stage.

Although the internal shielding prevents feed-back through the interelectrode capacities of the tube, this is only *one* source of coupling between stages. The input circuit must be shielded from the output circuit. The amount of shielding

necessary depends on the voltage amplification per stage and the circuit design. A metallic shield enclosing each tuned stage is usually sufficient. It may be necessary, if the voltage amplification is high, to place a grounded metal cap over the tube and also over its base.

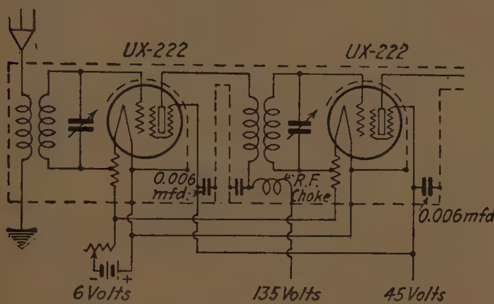


FIG. 156.—Radio-frequency amplifier in screen-grid tube circuit.

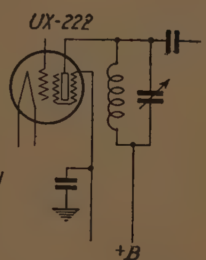


FIG. 157.—Optional interstage coupling in Fig. 156.

Use as an Audio-frequency Amplifier.—The tube may be used as an audio-frequency amplifier with resistance coupling. The connection is the same as for radio-frequency amplification as just described, except that the screen-grid voltage is lowered to compensate for the voltage drop in the resistances. A voltage amplification of 35 per stage may be obtained with perfectly flat frequency characteristics from above 10,000 cycles down to 50 cycles.

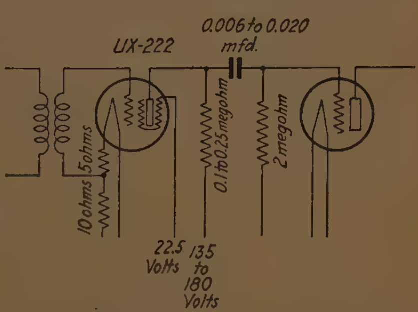


FIG. 158.—Audio-frequency amplifier in screen-grid tube circuit.

Information on the UX-222 is given in the circuit diagram in Fig. 156 which shows a radio-frequency amplifier circuit and an audio-frequency amplifier circuit. The shielding around the tube depends upon the arrangement of the parts and upon the degree of amplification. A shielded plate lead may be sub-

stituted for the shielding. The use of the radio-frequency choke coil, as shown in Fig. 156, is optional. The sizes of by-pass condensers specified are the minimum values and larger sizes are preferable.

Storage Battery Vacuum Tubes, Type UX-201A.—The UX-201A tube is a high-vacuum tube of the general-purpose type provided with a standard UX base. The UX-201A filament is of the thoriated-tungsten type. When the tube is used at moderate plate voltages, the filament voltage can be lowered to 4.5 or 4.0 volts without impairing efficiency and with an increase in life.

Five tubes or more may be operated from one 2-ohm rheostat used as a master control to reduce the filament voltage to 5 volts. Separate rheostats can be used to further reduce the filament voltage on any individual tube, as is often customary for volume control. When one tube is operated from a separate rheostat, the 10-ohm size is convenient although for volume control a resistance up to 25 ohms is desirable.

Operation as a Detector Tube.—Any plate voltage between 22.5 and 67.5 volts may be used. Critical adjustment of the filament voltage or the plate voltage is not necessary. Sometimes microphonic action is present when the filament voltage is below the rated value. The use of a cushioned socket for the detector tube is good practice when a power-amplifier tube is used in the stage supplying the loud speaker. The greater intensity of sound vibrations from the loud speaker subjects the detector to increased vibration and may result in "howling."

A grid leak of 2 megohms and a grid condenser of 0.00025 microfarad are recommended. Higher values of grid leak give better signal strength on weak signals but may result in blocking or distortion on strong signals.

Operation as an Audio-frequency Amplifier.—The low output impedance of this tube is the reason for its excellent performance in the audio stages of a receiver, especially with the improved types of audio transformers. Generally, 90 volts are used on the plate with a grid voltage of −4.5 volts. In all except the last audio stage, lower voltages may be used

without appreciably affecting quality and with a saving in "B" battery current. This saving is shown in the following table:

"B" Battery Current and Power Consumption

"B" battery voltage, volts	"C" battery voltage, volts	Plate current, milliamperes	"B" power consumption, milliwatts
45	−1.5	0.9	4
67.5	−3.0	1.5	10
90	−4.5	2.0	18
135	−9.0	2.5	34

When a power amplifier tube with low-amplification factor (type UX-171A) is used in the output stage, the plate voltage on the preceding tube (if UX-201A type) should not be below 67.5 volts to avoid overloading that tube before the output tube is delivering full power. The UX-240 tube is preferable to the UX-201A for use in the modern resistance-coupled audio amplifiers.

Use as a Power Amplifier.—In using the UX-201A tube as a loud-speaker supply tube, best results are obtained with a plate voltage of 135 volts, and a "grid bias" of 9 volts from the "C" battery. Some improvement in quality, with slight sacrifice in power output, is obtained with 7.5 volts of "C" battery voltage. Two UX-201A tubes in parallel on 135 volts have a power output equal to that of a UX-112A tube on 135 volts.

As "B" battery terminal voltages drop, the power output decreases because the "C" battery voltage remains constant. To obtain maximum battery service, the "C" battery voltage should be decreased 1.5 volts for every 12 volts drop in plate-battery voltage. If this is done, the "B" batteries may be used until their terminal voltage has dropped to between 30 and 35 volts per 45-volt battery block.

It is recommended that UX-112A, UX-171A, or UX-210 tubes be used as power amplifiers to supply the loud speaker where increased volume with undistorted quality is desired.

Use as Radio-frequency Amplifier.—The UX-201A tube finds its widest use in radio-frequency amplification, because of its high mutual conductance and high input impedance.

In radio-frequency amplification, a "B" voltage of 90 volts is used without the assistance of a "C" battery, and while this results in maximum amplification, it is wasteful of current. The addition of a "C" battery or a decrease in plate voltage to 67.5 or 45 volts results in a saving of "B" battery current, with improved quality on local programs. Two UX-201A tubes as radio-frequency amplifiers require 12 milliamperes plate current with 90 volts "B" voltage, 7.0 milliamperes with 67.5 volts, and only 3.4 milliamperes with 45 volts. The use of lower plate voltages may double the service obtained from dry cell "B" batteries, and aids in securing quiet operation from "B" battery eliminators.

Special Alkali-vapor Detector Tube, Type UX-200A.—The vacuum tube known as type UX-200A is for detector service only. In sensitivity it is superior to the UX-200 when the latter is critically adjusted. It attains this sensitivity without critical adjustment of the filament or the plate voltage. The filament is the same as in type UX-201A tube. A finer mesh is used for the grid to provide a higher amplification factor and, thus, greater detector sensitivity. The alkali vapor in the tube occasionally activates the filament to an unusual degree. This causes a whistling noise which is unaffected by the position of the loud speaker or by acoustic feed-back. To correct this condition, the filament should be operated for 1 minute at 10 volts. A cushioned socket is recommended.

When receiving a powerful local station at full volume, no marked increase in the strength of reception is noticed when type UX-200A tube is substituted for a UX-200 or a UX-201A tube. On distance reception there is an improvement in signal intensity and in reproduction due to the greater response obtained from the UX-200A tube on weak signals. A signal which is inaudible on a UX-201A tube is brought in with good volume on a UX-200A tube. The increased audibility approximates that from an extra stage of radio-frequency amplification.

The UX-200A tube decreases selectivity slightly but certain modifications result in improvement. Thus, without sacrifice in volume, the antenna may be more loosely coupled to the receiver. This diminishes interference from local stations. A shorter antenna may be used without loss in audibility as compared with the UX-201A tube and with a gain in selectivity. A hiss, caused by the formation of the vapor, is produced when the tube is first lighted and continues until the tube warms up. The usual 0.00025-microfarad grid condenser and 2-megohm grid leak are satisfactory. The preferred connection for the grid return is to the negative filament. The same sensitivity with improved quality is possible with grid-bias detection. Best quality of reproduction and maximum sensitivity are obtained with 45 volts on the plate. Plate voltages greater than 45 volts cause an undesirable increase in the plate impedance; with plate voltages less than 45 volts, the detector action decreases rapidly and noise may result.

Special Purpose Detector and Voltage Amplifier, Type UX-240.—Type UX-240 is designed to take advantage of the desirable characteristics of resistance coupling and to overcome the limitations. It does not replace other tubes for such service unless changes are made in circuit constants, as explained below. Grid spacing differs from that of the UX-201A tube, to secure the higher amplification factor ($u = 30$). Plate resistance is much higher, averaging 60,000 ohms at 135 volts at the plate and 1.5 volts at the grid, without a resistance in the plate circuit. With 0.25 megohm in the plate circuit, the plate resistance of the tube is 150,000 ohms.

Use as a Detector.—The UX-240 tube is between UX-201A and UX-200A in detector sensitivity. Either a UX-200A or a UX-240 tube may be used as the detector with resistance-coupled amplifiers. The UX-200A tube is preferred when two audio stages only are used, particularly when a UX-171A type is the output tube. When there are three audio-frequency stages in the receiver, the UX-240 tube should always be used as the detector. For protection against microphonic action, a cushioned socket is desirable. To obtain regeneration

when a UX-240 tube is used as a detector, closer tickler coupling is necessary than with tubes having lower plate resistances.

Good performance is obtained from the UX-240 as a detector with transformer coupling, although the low frequencies may be slighted unless the transformer has a high primary impedance. When the tube is so used the plate voltage should be increased to 67½ or 90 volts.

With a UX-240 tube used as a detector, and the resistance units specified below, no separate detector "B" tap is necessary, the same voltages being applied to all audio stages. Either grid-leak or grid-bias detection may be used. The former gives higher sensitivity and the latter freedom from distortion on high signal input voltages.

Grid-leak detection			Grid-bias detection		
"B" voltage, volts	Plate coupling resistance, ohms	Grid leak, megohms	"B" voltage, volts	Plate coupling resistance, ohms	Grid bias, volts
135 to 180	250,000	2 to 5	135	250,000	−3.0
....	....	....	180	250,000	−4.5

Use as Audio Amplifier.—When a UX-240 tube is used, its amplification factor of 30 allows maximum voltage amplification consistent with flat frequency characteristics. Oscillation or "motor-boating" of the amplifier may be prevented by selecting the circuit constants so as to make the amplifier less efficient at low frequencies. This may be done by the use of a low-resistance grid leak across each input stage, with a relatively small blocking condenser. A better method is to prevent the voltage developed across the common impedance from feeding back to the preceding stages. One arrangement is shown in Fig. 115, page 166. The series resistance R_s placed in the detector plate lead, or in the common lead to the detector and first audio-frequency stage when three stages are used, is shunted by large condensers, C_s. This forms a "trap" which, at very low frequencies, prevents any voltage developed in the output stage from feeding back to the first or second stage, and so prevents oscillation or distortion.

The values have been selected so that average "B" power units give satisfactory operation with the amplifier. With dry cell "B" batteries a smaller resistance, 0.05 or 0.025 megohm, may be used at R_s. This system does not affect amplifier performance over the range of frequencies essential for good reproduction. It causes a small decrease in amplification at 30 cycles and at higher frequencies it reduces slightly the plate voltage on the detector and first stage of audio-frequency amplification. Since the input voltage to these stages is low, this change in voltage is inappreciable.

The recommended values for the circuit constants of resistance-coupled amplifiers with UX-240 tubes are,

Blocking condenser..................	0.006 microfarads
Plate coupling resistance.............	0.25 megohms
Amplifier grid leak..................	2.0 megohms

"B" battery voltage, volts	Plate coupling resistance, ohms	"C" battery voltage, volts
135	250,000	−1.5
180	250,000	−3

UX-112A Vacuum Tube Type.—The UX-112A tube may be used in the detector and the first audio-frequency sockets of some receiving sets, with improvement in quality. No changes are necessary when this tube is installed in receivers in which the recommended "C" battery voltages are provided. The oxide-coated filament takes a current of 0.25 amperes.

Use as a Detector.—On detection service the UX-112A tube is efficient and quiet. A plate voltage of 45 volts, a grid condenser of 0.0025 microfarad, and a grid leak of 2 to 3 megohms, are satisfactory. On loud signals the grid-bias method of detection may be used. The heavy filament prevents microphonic action due to acoustic feed-back from the loud speaker. The low plate resistance gives improved frequency characteristics, particularly at the lower frequencies.

Use as a Radio-frequency Amplifier.—The plate voltage should not exceed 67½ volts unless a "C" battery is provided. When the UX-112A tube is used in a neutrodyne circuit the

neutralizing condenser must be adjusted to a higher setting. Similar precautions may be necessary to prevent oscillation in tuned radio-frequency amplifiers. An increase in the size of the series grid resistance if used, or fewer primary turns on the interstage transformer, may be necessary for stable operation.

When the circuit is adjusted, the low plate resistance of the UX-112A tube allows greater amplification per stage and greater selectivity is possible through a reduction in coupling. With loose coupling, the resistance coupled into the tuned output circuit is reduced, increasing the sharpness of resonance.

Use as Audio Amplifier.—The characteristics of the UX-112A are suitable for transformer-coupled audio-frequency amplification. The plate current is higher than that of the UX-201A tube, and this requires consideration of the audio-transformer design. Some transformer cores saturate easily, and the expected improved performance from the low output resistance is not obtained.

Use as a Power Amplifier.—The UX-112A tube serves in many installations as a power amplifier. The "C" voltage may be obtained from power supply devices without appreciable increase in transformer voltage. The plate current may be supplied from dry-cell "B" batteries or from small "B" power supply devices. In general, a tube having a very low plate resistance is desirable for "feeding" into a loud speaker, so that where the voltage and current requirements of the tubes with low amplification factors can be met, they are preferred.

Power Amplifier, Type UX-171A.—The UX-171A tube is a power amplifier designed to secure high quality of reproduction when used as a loud-speaker supply tube. This result is obtained with moderate voltages, from 90 to 180 volts, and tube distortion is practically eliminated.

At least one audio-frequency stage must precede the UX-171A tube in a receiving set as the tube requires a high input voltage. If the detector tube operates directly into the UX-171A tube, overloading of the detector tube occurs before the

UX-171A tube is producing a satisfactory volume. This tube will not operate as a detector or voltage amplifier. The spacing of the grid wires is made wide to obtain a low-amplification factor.

With operation at 135 volts the tube becomes fairly hot, but unusual heating indicates excessive plate voltage or reduced grid voltage. The correct grid voltage and the average plate current for this tube for various plate voltages are given in the table on page 108. With plate voltages over 90 volts, an output transformer having a 1 to 1 ratio of the windings and a low primary resistance, or a combination of low-resistance choke coil and by-pass condenser, should be used. This keeps the high direct current of the plate circuit out of the windings of the loud speaker. It prevents overloading the coils, and avoids the drop in "B" battery voltage caused by the resistance of the loud-speaker windings. An "average" loud speaker having a resistance of 1,500 ohms causes a drop of 15 volts on a 10-milliampere plate current, and of 30 volts on a 20-milliampere current. In view of the relatively high cost of "B" battery current, precautions to prevent this loss in voltage are worth while.

Vacuum Tubes for Alternating Current. Type UX-226.—This is a general-purpose amplifier tube, similar in characteristics to the UX-201A tube. With proper circuit arrangements, alternating current can be supplied directly to the filament. A standard UX base is used. The filament is of the oxide-coated type. While it is possible to use this tube for grid-bias detection, it does not give satisfactory results. The ripple voltage or "hum" of the UX-226 is several times as great as that of the UX-227 tube. The filament can withstand ordinary fluctuations in line voltage. The step-down transformer should be designed so that the normal voltage is slightly under 1.5 volts, a rheostat then being unnecessary. Primary taps or a primary rheostat may be provided to compensate for wide ranges in line voltage. The filament is suited for series operation from direct-current power sources, no filtering being necessary. This tube may then be used also as a detector.

Operation as an Amplifier.—The UX-226 tube gives about the same performance as the CX-301A tube when used as a radio-frequency amplifier. A "C" battery voltage (grid bias) *must* be used on alternating current operation to avoid an uneven flow of grid current. An uneven flow results in modulation and distortion of the incoming radio-frequency

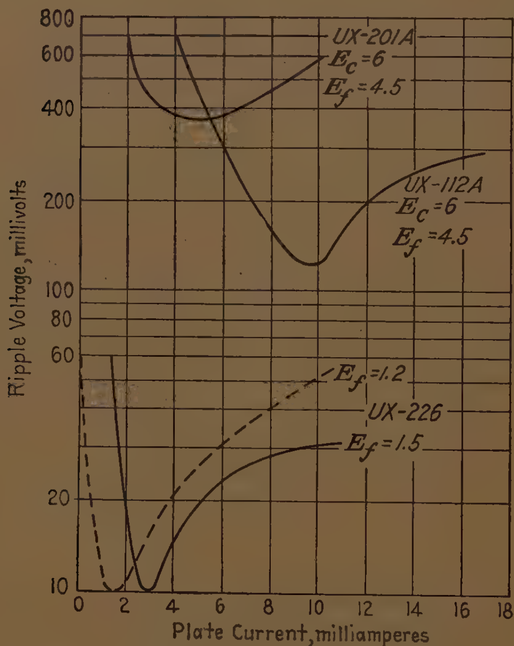


FIG. 159.—Variation of ripple voltage or "hum" with plate current for several tubes.

signal, together with decreased amplification. When the recommended grid-bias voltage is used, the ripple voltage is so low that modulation of the carrier is not appreciable, unless there is oscillation in the radio-frequency stages. The radio-frequency grid returns are connected to the electrical center, or neutral point, of the alternating-current supply because, otherwise, a 60-cycle voltage is impressed on the grid. Because of the rapid increase in ripple voltage with departure

from the current balance point, it is preferable to connect the grid return to the slider of a low-resistance potentiometer placed across the filament windings. Individual tubes may require a variation of 5 per cent from the exact center setting, and line conditions may sometimes require wider variations.

As shown in Fig. 159, the hum is a minimum at a plate current of about 3 milliamperes. The recommended grid-bias voltage allows a plate current of 3 to 4 milliamperes. Figure 160 shows a typical circuit diagram for UX-226 and UY-227 tubes in a receiver operated with alternating current. A

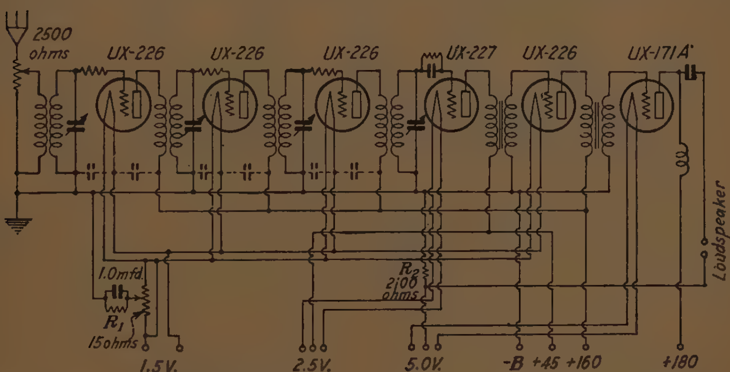


FIG. 160.—Typical circuit diagram for radio receiver using UX-226 and UY-227 tubes operated by alternating current.

15-ohm potentiometer is connected across the filament supply to the UX-226 tubes to compensate for small changes in circuit performance, in line conditions, and in tubes. The resistance R_1 in series with the potentiometer slider carries the plate current from the UX-226 tubes. The voltage drop across this resistance provides the required grid-bias voltage. The value of this resistance depends upon the number of UX-226 tubes and the net plate voltage which is equal to the applied plate voltage minus the voltage drop across the biasing resistance. In the circuit of Fig. 160, a grid-bias voltage of 12 volts is satisfactory because the net plate voltage then is 160–12 or 148 volts. If the plate current of one UX-226 tube is 4 milliamperes, the total current for four tubes is 16 milliamperes.

Then, by Ohm's law, the required resistance to produce a drop of 12 volts is 12 ÷ 0.016 or 750 ohms. The advantage of this arrangement is that the grid-bias voltage varies with the plate voltage. The resistance R_2 of 2,100 ohms carries the plate current of the UX-171A tube. The voltage drop across R_2 provides the grid-bias voltage necessary for that tube. A separate by-pass across R_2 is not necessary because the choke coil and condenser permit the audio component of the plate current of the power tube to pass through the loud speaker and to return to the filament.

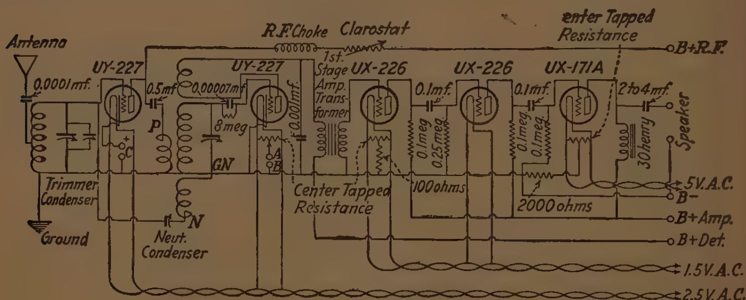


FIG. 161.—Circuit diagram using UX-226 and UY-227 tubes in Browning-Drake radio receiver.

The grid and plate returns are connected to a center tap on the transformer windings for the UX-171A and UY-227 tubes as shown in the figure. Or it is possible to make the connection to a resistance of from 20 to 50 ohms tapped in the center. The latter is often more convenient as the resistance may be placed close to the tube, making a short direct connection requiring one less lead between transformer and receiver.

The by-pass condensers, shown in dotted lines in the radio-frequency stages in Fig. 160 may be required to prevent coupling between stages, but may not be necessary if a low-resistance potentiometer is used. A control of volume may be obtained by reducing the antenna coupling, or by connecting a resistance potentiometer across the condenser in the first tuned stage, the grid being connected to the slider. A rheostat used in the filament circuit to obtain volume control or a series resistance in the plate circuit increases the ripple voltage.

Either method may result in modulation of the radio-frequency signal.

If the "B" power unit is in the cabinet with the receiver, the transformer and choke coils must be shielded to prevent pick-up of the 60-cycle hum by the audio transformers and the wiring of the receiver. The filament circuits should be wired in twisted pairs to reduce stray pick-up currents. Figure 161 shows the use of UX-226 and UY-227 tubes in the Browning-Drake receiver.

Vacuum Tube, Type UY-227.—This is a detector and amplifier tube similar in characteristics to the UX-210A tube. It is used as a detector with UX-226 tubes in receivers operated with alternating current. The fifth prong on the base is the cathode connection.

The usual filament is replaced by an indirectly heated *cathode* consisting of an oxide-coated metal cylinder which is heated by an internal filament insulated from the cylinder. The filament is of tungsten, and may be operated with alternating current. The fluctuations in temperature with each alteration of the current at the rate of 120 cycles per second are prevented from affecting tube performance by the thermal inertia of the insulating material and of the cylinder.

The socket must make good electrical contact with the heater filament prongs as the current required by the heater is high and the filament voltage is low. If appreciable contact resistance exists, the current supplied may be too low for satisfactory operation. The filament supply arrangements may be similar to those for UX-226 tubes except that the transformer voltage should be 2.25 volts. Filament voltages which are more than 2.5 volts shorten the life of the tube. A rheostat which can carry 2 amperes may be used in the filament circuit to reduce the voltage.

Use as a Detector.—The usual grid leak and condenser are required, or grid bias (see page 129) detection may be used. The amount of ripple voltage (hum) is not greatly affected by the type of circuit. To keep ripple voltage at a minimum, the center tap of the transformer should be connected to the detector tap, placing 22½ or 45 volts between the heater fila-

ment and the cathodes as shown in Fig. 160. The ripple voltage is only a few millivolts. When followed by normal audio amplification, the ripple is inaudible at some distance from the loud speaker. A potentiometer return may be used in place of the transformer tap but the slight change in ripple voltage with the position of the potentiometer slider usually makes this unnecessary.

The detector grid return is connected directly to the cathode. The entire cathode is at the same potential and, as a result, sufficient grid current for satisfactory grid-leak detection is established through the flow of electrons to the grid, due to the velocity of emission from the cathode. The UY-227 tube is free from microphonic action and a cushioned socket is seldom required.

Power Amplification Tube, Type UX-210.—The UX-210 tube is now used instead of the older UV-202 tube for direct-current service. A standard UX base is provided. The filament of the thoriated tungsten type is usually heated with alternating current by means of a step-down transformer designed for the proper filament voltage (7.5 volts). The filament current is 1.25 amperes.

Use as Power Amplifier.—The principal use of the UX-210 tube in broadcast reception is in heavy-duty power-amplifier equipment, as a supply tube for a loud speaker. Different output characteristics can be obtained by the selection of the proper ratio of turns in the output transformer which is needed. This not only keeps the direct current of the circuit out of the loud-speaker windings, but also provides insulation against the high plate voltage of 350 to 425 volts. If the impedance of the electrical load is low, a step-down ratio, properly chosen, permits delivery of maximum undistorted power from the tube. The power available (1.5 watts maximum) is considerably in excess of that obtainable from other types of tubes. The available power is more than adequate to permit the maximum volume for ordinary service conditions to be obtained from heavy-duty loud speakers. Thus, in normal service a large reserve sound volume is available, and the tube is operated below full capacity, a condition

favorable to the best reproduction. Operation with a plate voltage less than 200 volts is not recommended, the UX-171A or UX-112A tubes being preferable for service at the lower voltage.

Full-wave Rectifier, Type UX-280. Half-wave Rectifier, Type UX-281.—The UX-280 tube is a *full-wave* rectifier. It consists of two plates, or anodes, with a filament section for each. The maximum permissible direct current is 125 milliamperes, and the maximum alternating-current voltage is 300 volts (effective value) per anode. This tube may be used to replace the UX-213 tube in devices designed for that tube, and with slightly greater output.

The UX-281 tube is a single-anode type for *half-wave* rectification. The maximum permissible direct current is 85 milliamperes with a maximum alternating-current voltage of 700 volts (effective value). When two UX-281 tubes are used in a full-wave circuit, the maximum direct current is 170 milliamperes. The tube may be used for replacement in equipment designed for UX-216B tubes. The UX-280 and UX-281 rectifier tubes are of the oxide-coated filament type. The UX-280 tube is rated at 5 volts of filament voltage, with a variation of 10 per cent. This is an adequate variation requirement since the line voltage commonly varies between 105 and 125 volts, and the nominal value is 115 volts.

A battery eliminator must deliver uniform voltage under varying conditions of current requirements. The important factor in obtaining satisfactory current regulation is low internal resistance in the rectifier tube. High internal resistance causes the output voltage to vary rapidly with small changes in the current. Because of the low internal resistance of the UX-280 tube, a transformer supplying a secondary terminal voltage of 220 volts will furnish a direct current of 65 milliamperes at 220 volts at the input of the filter, the voltage at the output of a 1,000-ohm filter being 150 volts. Higher output voltages are available with lower current requirements or higher transformer voltages.

To obtain a smooth direct-current output from a battery eliminator, filter circuits are necessary. The requirements

of these circuits are minimized by the use of filament-type rectifiers. There is no arcing or sparking when type UX-213 or type UX-216B tubes are used, and hence there is no tendency to set up radio-frequency surges or impulses.

Rectifier Circuit Design.—Rectifier circuits for the UX-280 tube are shown in Figs. 162 and 163. The values of the

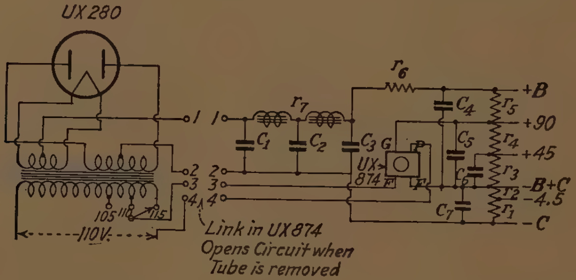


Fig. 162.—Common type of rectifier and filter for UX-280 tube.

inductances and condensers in the filter circuit as given in the table below vary with several factors. The most important one of these is the amount of ripple voltage which can be allowed. Other factors are the maximum current of the

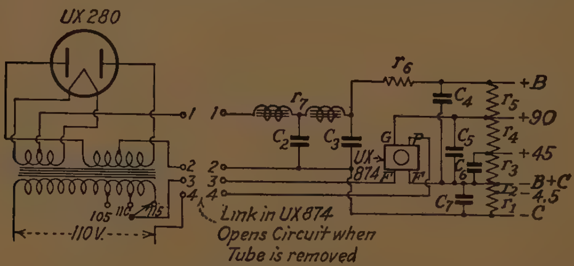


Fig. 163.—Common type of rectifier and filter for UX-280 tube with input condenser C_1 omitted.

"B" battery eliminator and the frequency of the line supplying the alternating current.

The circuit diagram of one common type of rectifier and filter is shown in Fig. 162. With this circuit, the load on the tube is heavy, as shown on the oscillograph record in Fig. 164, which indicates instantaneous values of the current in

Select r_1, r_2, and r_3 for the power tube of type and voltage desired						Select r_6 and r_7 for the transformer and power tube type. Select r_6 for the chokes (r_7 is the total choke resistance)							
						Filter circuit in Fig. 162, condenser input				Filter circuit in Fig. 163, choke input			
							Total rectified output[1]				Rectified output[1]		
Power tube type	$+B$, volts	$-C$, volts	r_1, ohms	r_2, ohms	r_3, ohms	Transformer secondary volts, per anode effective	D.c., volts	D.c., milliamps	$r_6 + r_7$ ohms	Transformer secondary volts, per anode effective	D.c., volts	D.c., milliamps	$r_6 + r_7$ ohms
1-UX-112A	160	−11.5	110	71	1,270	220	226	63	865	270	215	63	690
						260	271		1,375	320	250		1,370
						300	327		2,470	370	303		2,090
1-UX-171	133	−27.0	317	63	818	220	217	71	773	270	210	71	777
						260	263		1,420	320	253		1,280
						300	320		2,230	370	297		1,900
1-UX-171	180	−40.3	480	60	1,635	220	214	75	.....	270	208	75	
						260	260		327	320	252		420
						300	317		1,285	370	295		995
2-UX-171	160	−34.5	330	49	1,270	220	200	91	60	270	198	91	38
						260	248		587	320	243		333
						300	302		1,180	370	283		995
1-UX-210	250	18.0	200	67	2,900	220	222	67	.....	270	212	67	
						260	268		0	320	256		
						300	323		820	370	300		477

[1] These values of direct-current (d.c.) voltage and current from the output curves of UX-280 tube shown in Figs. 166 and 167.

r_3 = 10,000 ohms C_1, C_2, C_3 = 4 microfarads.
r_4 = 8,000 ohms C_4 = 2 microfarads.
C_5, C_6, C_7 = 1 microfarads.

NOTE: The +90 volts remains constant for any current not exceeding 40 milliamperes.
r_6 prevents excessive voltage at the +B tap.
r_7 is the total direct-current resistance of the choke coils.

the tube. This record shows that a current flows through the tube only when the transformer voltage exceeds the first filter condenser voltage. The charging of the first condenser in the filter causes a very heavy current to flow through the tube for a short time, reaching a peak of 310 milliamperes. Since the average current (load current) is only 125 milliamperes, the peak current through the tube reaches a value of two and five-tenths times the average current. Thus, the

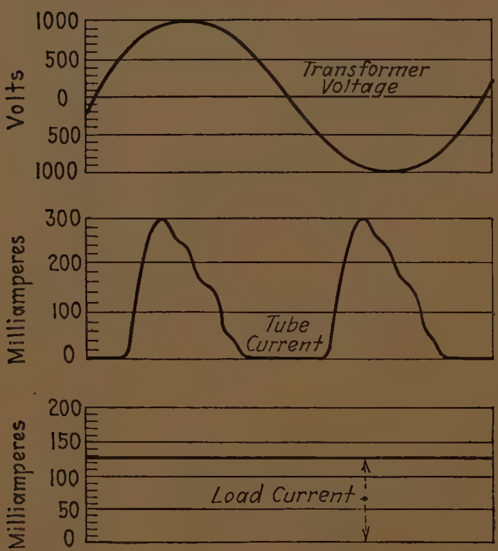


FIG. 164.—Oscillograph record of UX-280 tube with large load current.

filament must be heavier and longer than would be the case if the rectified current could flow for a longer time, so that the high peak could be avoided.

A reduction in the value of the peak current is obtained by means of the filter circuit in Fig. 163, where the first filter condenser is omitted and the tube feeds directly into the inductance or choke coil. The oscillograph record (Fig. 165) shows the reduction in peak current, which is only 140 milliamperes or one and one-tenth times the "load" current. This reduction is possible because the tube no longer feeds

directly into a condenser, and the choke coil keeps the current flowing through one anode or both during the entire cycle. Some voltage is lost in the choke coil, which, however, is a reactance load and does not consume power. The efficiency of the two systems is almost the same. The values below bring out the advantages of the latter circuit in tube operation. Operation at this reduced peak current extends the life of the

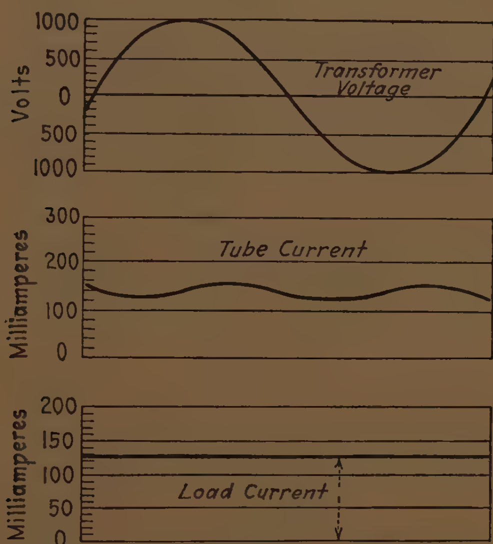


FIG. 165.—Reduction of peak tube current by omitting first filter condenser in Fig. 162.

filament of the tube and allows a lower value of emission before the operating efficiency of the tube is affected. A tube having an emission of 200 milliamperes could be used satisfactorily in the circuit of Fig. 165 but not in that of Fig. 164.

The condenser which is used across the input circuit in Fig. 162 should be added across the output of the filter of the circuit in Fig. 163 since the ripple voltage is slightly greater than that from the usual filter.

The higher efficiency in the second case is the result of reduced tube losses because of operation at a lower tempera-

ture. As shown in Fig. 167, the regulation is better than when a condenser is used, except at very low values of power output.

OPERATING CONDITIONS

Circuit	Transformer, volts	Power input, watts	Load current, milliamperes	Load, volts	Power output, watts	Efficiency, per cent
Fig. 162	300	62	125	300	37.5	60.5
Fig. 163	360	59.5	125	300	37.5	63

A filter system, in which the input filter condenser is omitted, is not recommended for half-wave rectification, because output current and voltage are reduced considerably and the operation of the filter is impaired. The usual circuit design with a small input condenser of about 1.0-microfarad capacity reduces the peak current of the tube without noticeably reducing the output voltage.

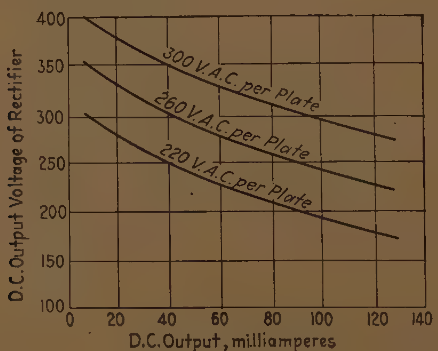


FIG. 166.—Direct-current output of UX-280 tube in rectifier circuit (condenser input).

Figure 166 illustrates the regulation curves of the voltage delivered to the filter input by the UX-280 tube at various load currents with the type of filter in Fig. 162. If the filter resistance is known, the output voltage at the filter terminals can be determined. Figure 167 gives regulation curves which show the advantages, at load currents greater than 20

milliamperes, that are obtained by using the circuit connections in Fig. 163.

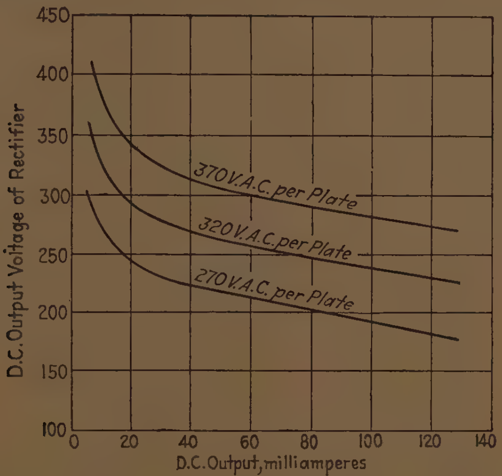


FIG. 167.—Direct-current output of UX-280 tube in rectifier circuit (choke coil input).

The full-line curves in Fig. 168 show the regulation of two UX-281 tubes in a full-wave rectifier with a conventional

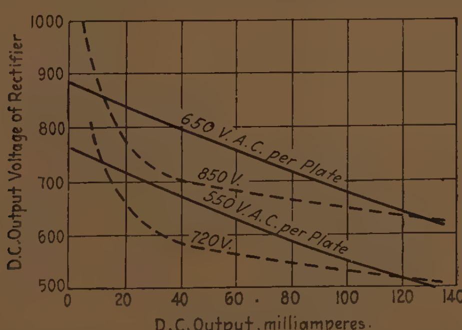


FIG. 168.—Direct-current output of UX-281 tube in full-wave rectifier. Curves in full lines show condenser input, those in dotted lines show choke coil input.

filter. The dotted lines show the performance obtained in a similar circuit in which the first filter condenser is omitted. The superior regulation of the performance obtained with the

use of the choke-input coil is evident. The circuit in which the first filter condenser is omitted is not satisfactory when the tube is used as a half-wave rectifier. The curves in Fig. 169 show the voltage delivered by the tube at the input to the filter with the usual filter circuits.

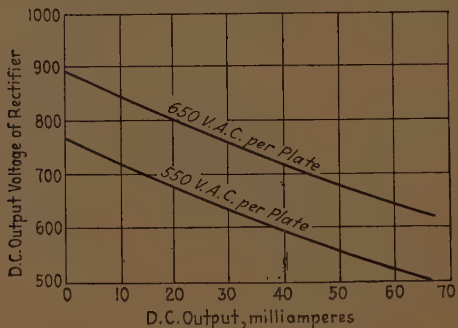


FIG. 169.—Direct-current output of UX-281 tube in half-wave rectifier circuit.

Output-voltage Regulator or Glow Tube, Type UX-874.—This is for service in "*B*" *battery eliminators* where great flexibility in output current is required or where the alternating-current line voltage varies widely. It is particularly valuable in eliminators with various voltage taps. When a UX-112A or a UX-171A tube is used with a UX-201A tube, the eliminator must supply from 120 to 180 volts with a maximum current drain of 20 milliamperes from this tap, together with a 90-volt tap averaging 20 milliamperes, and a detector 45-volt tap with a maximum requirement of about 3 milliamperes. The use of high and variable series-resistance units to obtain these voltages has not been entirely satisfactory. The resistance units may become noisy or burn out and are not effective until current is established in them. When the eliminator is turned on, with the receiving set off, the voltage across the "B" terminals may rise to very high values with the possibility of damaging the by-pass condensers.

The glow tube insures proper voltage regulation of the "B" battery eliminator. It also improves the filter action since it acts as a low-resistance path for the residual ripple

voltage from the filter. This is equivalent to extra filter capacity across the output. It is effective in this respect at very low frequencies and thus eliminates the possibility of interstage coupling. For this reason, the tube is useful with amplifiers which are efficient at low frequencies, as the tendency toward instability resulting in distortion and "motor-boating" is eliminated.

The UX-874 tube accomplishes voltage regulation from its characteristic that on any current flow from 10 to 50 milliamperes it develops a constant voltage averaging 90 volts. The tube cannot be used without a series resistance to limit the current to a value of 50 milliamperes, which occurs when the receiving set is turned off and the "B" eliminator is left on. The use of this tube in the usual type of eliminator to regulate the voltage at the 90-volt terminal on the receiving set is shown in Figs. 162 and 163.

In operation, the tube shows a glow surrounding the cathode, which in this tube is a large circular plate. If the tube connections are reversed, a bright glow occurs at the small terminal. Proper results are not obtained unless connections are made as in the diagram. The terminals which would normally be "F" are connected together in the base of the tube and this short-circuited connection may be used as a line switch in the transformer primary. Then the "B" battery eliminator cannot be turned on until the UX-874 tube is inserted in the socket nor can the tubes be interchanged with the possibility of being damaged. If a rectifier or "power" tube is inserted in the UX-874 socket, the transformer primary remains open and no current flows to the equipment. Two UX-874 tubes may be placed in series to obtain 180 volts, a center tap between the two tubes then providing 90 volts.

Line-voltage Regulator or Ballast Tube, Type UX-876.—A "ballast" tube like the one known as UX-876 is intended to regulate the input voltage to the primary winding of the transformers used in "B" battery eliminators. The tube passes 1.7 amperes at any applied voltage between 40 and 60. The current in the secondary winding of the transformer must be

such as to bring the voltage on the tube to 50 volts at normal line voltage. If the line voltage averages 115 volts, the transformer, under load, should be designed to take 1.7 amperes at 65 volts, the remaining 50 volts being required by the "ballast" tube. If the line voltage drops or rises 10 volts, the voltage across the "ballast" tube changes accordingly and the transformer primary voltage remains practically constant at 65 volts. The tube requires several minutes to be heated to constant temperature. The voltage drop increases rapidly for the first 3 minutes and then slowly up to about 10 minutes, when the tube reaches its final temperature. During this interval the voltages on the tubes are slightly high, but do not exceed safe values. Thereafter, the "ballast" tube maintains the voltage practically constant. This tube will regulate the primary transformer voltage at frequencies from 25 to 60 cycles provided the transformer has been designed for the operating frequency. Equipment designed for 60 cycles cannot be used for 25-cycle operation, and *vice versa*. The tube should be protected by a ventilated metal housing for safety reasons in case a defective tube should explode.

Power Amplifier, Type UX-250.—The demand for greater undistorted power output consistent with good quality has led to the development of the UX-250 tube. This has a filament made of a material similar to the coated ribbon used in UX-171A or UX-281 tubes. The low temperature of operation and the large filament in the tube account for the small amount of ripple voltage which occurs when alternating current is applied to the filament. The rating of the filament is 1.25 amperes at 7.5 volts. The required current may be supplied from the 7.5 volt winding of a *power* transformer. The voltage across this winding should not exceed at any time a value of 7.9 volts which is equal to the rated value plus 5 per cent. The performance of the tube is not affected by a small amount of gas in the tube, if the resistance in the grid circuit is kept low. Circulation of air around the tube should be provided to prevent overheating. The plate of an overheated tube appears much brighter than the usual dull red color.

Use as an Amplifier.—The UX-250 tube is designed for operation at high plate voltages and has electrical characteristics similar to those of the UX-171A tube. Its use allows much greater volume to be obtained from suitable loud speakers. The UX-250 tube is capable of a maximum undistorted power output of 4.5 watts, the UX-210 gives 1.5 watts, and the UX-171A, 0.7 watts. Within the power range of each tube, however, there is no difference in quality.

If the desired volume is not greater than that which may be obtained from a UX-210 tube operated with a plate voltage of 425 volts, the UX-250 tube may be operated with a plate voltage of less than 300 volts; that is, for equivalent power output, the plate voltage necessary for the UX-250 tube is lower than that for the UX-210 tube. For the conditions mentioned, the *total* voltage required is the sum of the plate and grid-bias voltages. In the case of the UX-250 tube this is $300 + 54 = 354$ volts as against $425 + 35 = 460$ volts for the UX-210 tube. The use of the UX-250 in place of the UX-210 tube is not recommended unless the equipment is designed for the required high plate voltage and current and the necessary grid-bias voltage. The table on page 109 shows that the place current and the grid-biasing voltage of a UX-250 tube vary from 28 milliamperes and -45 volts at 250 volts on the plate to 55 milliamperes and -84 volts at 450 volts on the plate. The life of the tube will be a maximum when conservative plate voltages are used, the recommended values being between 250 and 400 and the limiting value 450 volts.

The high plate current can be supplied by one UX-281 rectifier tube or two for full-wave operation. This tube has an output rating of 85 milliamperes and, also, can supply the plate current for the other tubes in a receiving set. A rectifying transformer used to operate a UX-250 tube under load at its maximum plate voltage should have a secondary winding intended for at least 600 volts.

It is recommended that the grid-bias voltage be obtained from the voltage drop across a resistance in series with the "B minus" return wire as shown in Fig. 170. This connection

compensates almost completely for plate voltage changes which may occur because of line voltage variations. This action occurs because an increase in plate voltage causes a small increase in plate current which, in turn, increases the value of the applied grid-bias voltage sufficiently to compensate for the new value of plate voltage. The reverse of this action takes place if the voltage decreases when a sudden drain is put on the plate supply. In this way, the proper operating condition is maintained without change. The grid-bias voltage must be applied at all times while the tube is operating. If the grid circuit is open, the plate current

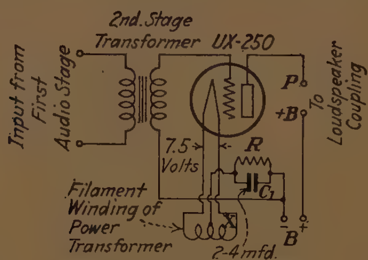


FIG. 170.—Method of obtaining grid-bias voltage for UX-250 tube from voltage drop.

increases so much that both the power tube and the rectifier tube are overloaded and the rectifier tube filament may be damaged.

Some designers use an adjustable center-tapped resistance device across the filament of the tube. The purpose of this is to allow an adjustment under actual operating conditions so that the hum may be reduced to a minimum. If this resistance is used, the wire in Fig. 170 marked "X" is connected to the movable arm of the device.

The UX-250 tube is not designed for use in resistance-coupled amplifiers. The resistance in the grid circuit should be kept low, the total resistance of the grid-filament circuit preferably being under 25,000 ohms. The usual transformer secondary in the input circuit gives a normal value of resistance in the grid circuit.

Some form of coupling must be inserted between the output circuit of the tube and the loud speaker. Such coupling is provided to prevent excessive voltage drop in the plate circuit and to protect the loud-speaker windings. This purpose is accomplished by the use of a speaker filter or a transformer as shown in Fig. 171. The filter consists of a low-resistance output choke with a condenser of suitable size; the transformer must be capable of handling the heavy plate current of the tube without saturation of the core or overheating of the windings. A device of this kind is *not* provided to adjust circuit impedances because the impedances of both the tube and the modern loud speaker are low in value.

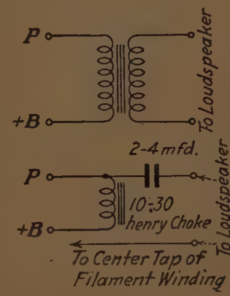


FIG. 171.—Suggested protective coupling between output circuit of tube and loud speaker.

A signal input voltage of about 60 volts (effective value) must be applied to the UX-250 tube when operated at its maximum plate voltage to obtain a maximum undistorted power output. Signal input voltages of 24 and 28 volts are needed for the UX-210 and UX-171A tubes, respectively. It is clear that considerable voltage amplification must be obtained between the detector and the grid of the power tube. A satisfactory voltage amplifier may consist of two stages of double-impedance coupling with UX-112A tubes, or of transformer coupling (6 to 1 ratio). The UX-112A tube is suggested in order to keep the impedance low. The so-called "push-pull method" is not suitable for use with UX-250 tubes because it takes double the input voltage needed for a single tube.

CHAPTER XI

SPECIAL INDUSTRIAL APPLICATIONS OF VACUUM TUBES

Until recently, there have been few applications of radio circuits and vacuum tubes to industrial or general manufacturing processes. This may seem remarkable in the face of the very great advances that have been made in radio telephony, especially for purposes of broadcasting and wireless telegraphy. Actually, the industrial applications are relatively simpler than those having to do with communication. For example, the radio receiving set, when tuned to a broadcasting station, takes out of the air an infinitesimal amount of electrical energy, and then must perform the service of amplifying the impulses due to this small amount of energy without distortion, so that, at a distant point either a small group or an immense audience can hear the words of the speaker. In the applications of radio circuits and vacuum tubes to industrial services, the device to be used can be supplied with any desirable amount of electrical energy, and, therefore, does not require the delicate amplifying arrangements that give most of the trouble in dealing with radio circuits used for telephony or telegraphy. In the applications of radio circuits to be described in this chapter, the vacuum tube plays an important part, and the necessary adjustments in service are made by a variable condenser in combination with a fixed condenser. The variable condenser is used to make the adjustments which are necessary to suit the device to the kind of work to be performed. The fixed condenser is used to measure the variations in the manufacturing process as varying conditions change the capacity effect between the fixed plates of the condenser.

In general, it may be stated that, in the industrial devices to be explained, the operating unit consists of two loosely coupled

radio-frequency oscillator circuits, one of the circuits being connected to the secondary winding of a transformer of which the primary circuit is fed by the first circuit. Indicating or recording instruments are provided which are responsive to the relative tuning of the secondary circuit, the means of relative tuning being controlled by the capacity effect of the product being measured. In other words, the primary circuit, as explained, corresponds to a *radio broadcasting station* which happens to be in the same box with the secondary circuit which corresponds to a *radio receiving set* which is not quite in the condition of being tuned in on the broadcasting station, but is tuned to a point somewhat off the resonant peak. In this relation of the circuits to each other when only the reception of sounds is being considered, as in broadcasting, a slight change in the position of the parts of a variable condenser will change the capacity effect to such an extent that louder sound reception will be obtained. On the other hand, in these industrial applications to be explained, instead of sounds which are broadcasted and received by the use of loud speakers or earphones, the action is observed by the deflection of the pointer of a sensitive ammeter which shows the strength of the current used for purposes of control.

Weighing and Measuring with Radio Currents.—Methods of determining weight and thickness with unusual precision depend upon the use of vacuum tubes applied in very much the same way as in the ordinary radio receiver. Applications for this purpose may be illustrated by the use of a variable condenser which is a part of the radio receiving set. The sensitivity of the variable condenser in the receiver to changes in the relation to each other of the moveable plates may easily be shown by placing a piece of tissue paper between two of the plates and observing the effect on reception. For example, if the dials of the receiving set have been adjusted so that the receiving set is tuned for the reception of the radio waves from a distant broadcasting station, and, then, a piece of very thin paper is placed between the plates of a variable condenser in the set, the reception from the broadcasting station which had been tuned in will fade, and if there is another

distant station operating at about the same wave length, the receiving set may now be observed to be tuned to it. The reason for this is that paper has a much higher dielectric constant than air, and, consequently, when a piece of paper is inserted between the plates of the condenser, its capacity is so much increased that the radio receiving set may be tuned to a broadcasting station transmitting on a somewhat higher wave length.

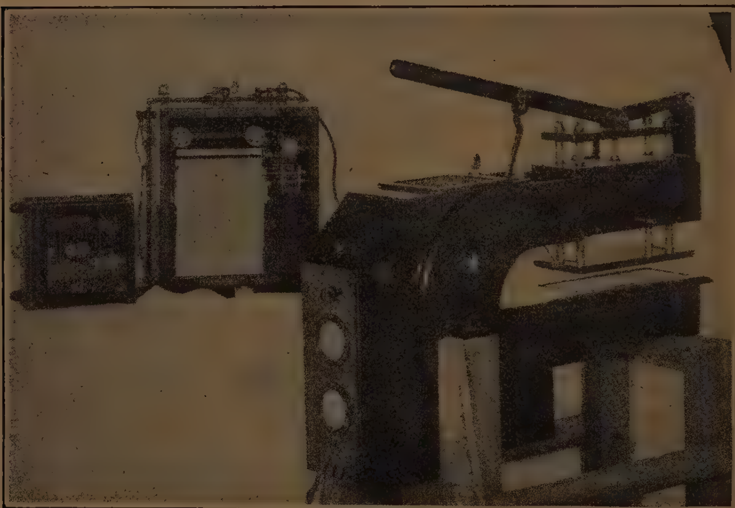


FIG. 172.—Application of radio equipment for accurate measurement of thickness of paper.

A regenerative receiving set tuned by the zero-beat method has been found to be very satisfactory for this kind of measurement, as very slight variations in the thickness of the paper between the condenser plates has a marked effect upon the tuning of the set. In its essential parts, a radio receiver for this kind of service consists of an oscillator vacuum tube (see page 202) and a tuned resonant circuit. The resonant circuit includes, preferably, both indicating and recording ammeters. This circuit may be tuned by altering the capacity of either of two condensers. One of these is a precision variable condenser which is used to bring the tuned circuit into reso-

nance with the oscillator tube when the materials being measured are of widely varying dielectric strength. The other condenser is of the fixed type shown at the ends of the arms of the instrument in Fig. 172. A strip of the material to be measured is passed between the plates of the fixed condenser when measurements are to be made. Any variation in the thickness or the weight of the material in the strip which passes between the plates of the fixed condenser will cause a variation of the capacity of the condenser, and, consequently, also a variation of the natural period of the tuned circuit. As the result of the variations of capacity and natural period of

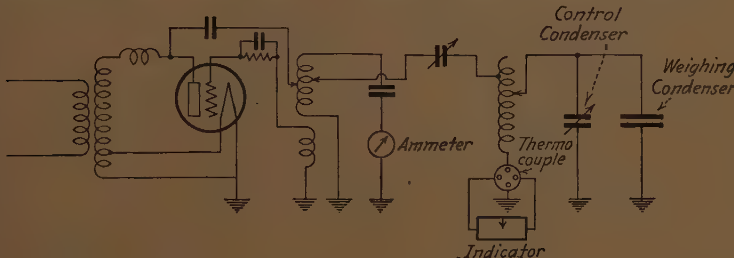


FIG. 173.—Circuit diagram of radio measuring device shown in Fig. 172.

the tuned circuit, there will be corresponding variations in the flow of the radio-frequency current flowing through the indicating meter which is arranged to show such variations. Now, if a strip of some material as, for example, a sheet of paper is passing between the plates of the fixed condenser, and the variable condenser is set to bring the tuned circuit to a "point" just off the resonance peak, then, any variation in the capacity of the fixed condenser, as the result of a variation in thickness or weight (and of the dielectric constant) of the paper, will produce a change in the circuit of the oscillator vacuum tube. The pointer of the indicating meter will then swing away from its central position in a direction depending upon whether there is an increase or decrease in the thickness or weight of the material of which the moving strip is made. A circuit diagram of this device is shown in Fig. 173.

In the use of the experimental apparatus which was first tried to demonstrate the practicability of this device, it was

found that the temperature of the room in which it was used had a considerable effect in changing the position of the metal parts so that the change in temperature would be recorded as a change in thickness or weight of the material being measured.

The temperature difficulties are avoided by using a massive cast-iron frame for the fixed condenser and providing columns made of Invar steel for supporting the plates of this condenser. By properly arranging the cast-iron parts and those of Invar steel, the variations in capacity effects due to temperature changes have been minimized to such an extent that they have no appreciable effect on the operation of the instrument.

Radio Apparatus for Moisture Control.—A radio device using vacuum tubes has been developed for the very accurate control of moisture in the manufacture of products which are made in sheets. The apparatus used for this purpose has the same general arrangement of circuits as the device already explained for the accurate measurement of thickness or weight of sheets of materials in the process of manufacture. For example, in the manufacture of paper, the moisture content of the sheets in the last stages of manufacture is important. Application is made of the variation of the capacity of a fixed condenser in the same way that the capacity varies with the thickness or weight of strips or sheets of paper passing between the plates. An apparatus of this kind is called a *precision hygrometer*. In this instrument, the measurements are made by an indirect method, that is, the change of moisture capacity of the material itself as it varies with moisture content is not measured. On the other hand, all the measurements are made of the moisture content of a ribbon of cellulose acetate which is stretched across the surface of the moving sheet in which the amount of moisture is to be determined. This ribbon of cellulose acetate, when passed over, but not quite touched by the surface of the sheet material being manufactured, is very sensitive to changes in the moisture of the manufactured sheet.

In the precision hygrometer operated by radio circuits, the moisture content of sheets of the manufactured product is used to vary the tuning of the secondary radio circuit in such

a way that the current in the circuit produces corresponding deflections right or left of the pointer of the indicating meter. In the operation of this device, a narrow ribbon of celluose acetate, which is very sensitive to the presence of moisture, is placed very close to the sheet of manufactured product, but is shielded on all other sides so that it is exposed only to the variations of moisture in the moving sheet passing near it. When the sensitive ribbon of cellulose acetate is placed in this way, its moisture content is directly responsive to that of the paper and to nothing else. Now, the effect of moisture on the cellulose-acetate ribbon is to change its length which becomes slightly greater when the amount of moisture is increased. In the device described, one end of the cellulose-acetate ribbon is fixed at one end and is attached at the other end to the movable plate of a fixed condenser which is connected into the secondary circuit of two transformer-coupled circuits. Changes in the moisture of the sheet of the manufactured product as it passes along over the shielded cellulose-acetate ribbon cause changes of length in the ribbon, which cause corresponding changes in the tuning of the condenser in the same way that the movement of the knob of a variable condenser changes its tuning. These changes of tuning by alterations of the length of the ribbon produce variations of the current in the secondary circuit in which the sensitive indicating meter is included. It is obvious, therefore, that moisture variations in the sensitive ribbon will affect the amount of current in the secondary circuit and, therefore, the indications of the pointer of the meter.

A variable type of condenser which is used for purposes of adjustment is in parallel with the fixed condenser, as described, which is used to control the amount of moisture in the manufacture of the product. This variable condenser is used to set the mid-scale reading of the instrument at the particular value of moisture content in the manufactured product that it is desired to hold. The sensitiveness of the instrument, that is, the number of increments of deflection of the pointer of the indicating meter for 1 per cent of change in moisture of the manufactured product, can be adjusted by changing the air gap of the fixed condenser. It will be understood that

these two adjustments are necessary in the setting up of the instrument or in the necessary changes which may be made to adapt it to different operating conditions as they relate to changes of product or to changes in specifications for moisture content. For example, the moisture content which is preferable for news print is much higher than for other grades of paper. Provision may be made so that the variations of the indicating meter are shown on a chart as a continuous record.

The most important advantage of using, as a guide, the continuous record rather than an indicating instrument is that any changes made by the operator of a machine may be based on the trend, as well as the present value, of the moisture content. The paper might be "on the dry side," but showing a progressive rise of moisture, and the operator might rightly conclude that it would become normal shortly if let alone. He is working much less in the dark than if he knows only the condition of the paper at the moment. The instrument is provided with electrical contacts that are closed by the pointer of the indicating meter whenever the moisture becomes too high or too low, and connected so that they will open an electrically actuated steam valve by a measured amount when the low-moisture contact is made, and close it by such an amount when the moisture content is too high.

Amplification of Currents in Telephone Circuits by Vacuum Tubes.—In every telephone circuit there is some transmission loss of energy and, consequently, also of sound value, which is technically called *attenuation*. The attenuation loss is due partly to the length of the circuit and partly to the losses in the various instruments and other devices which are included in the circuit. Audio-frequency amplifiers have been used with good results in reducing the attenuation in telephone circuits, and this reduction of attenuation in the circuit has been done much more cheaply than if so-called "load" inductance had been used. An audio-frequency amplifier in a telephone circuit has an effect which is exactly opposite to that of attenuation, that is, the audio-frequency amplifier delivers more electrical energy to the line than it receives from it. In other words, if the electrical energy at any point in a

telephone circuit should be increased, it is passed through some sort of device which gives energy back to the telephone circuit in much larger amount than was received; the amplification is in proportion to the increase in electrical energy. It is, of course, impossible to deliver more energy to the telephone circuit at any point than is received from the circuit at that point, unless some external source of energy is drawn upon. Amplification of telephone currents means the adding of energy from an external source to the energy already present at the point where amplification takes place. Before the invention of the vacuum tube for radio transmission and reception, a magnetic type of amplifier was in use on long telephone circuits to overcome the attenuation.

The invention of the vacuum tube as used in radio transmission and reception immediately suggested the application of this device as a substitute for the magnetic type of amplifier. Vacuum tubes of this kind are now an essential part of all the amplifiers used in modern telephone installations.

One of the simplest applications of the vacuum tube for amplification in telephone service is illustrated in Fig. 174, in which the vacuum tube is shown diagrammatically by the filament *F*, the plate *P*, and the grid *G*. An "A" battery is shown as it would be used for heating the filament *F*. The "B" battery has its positive terminal connected to the plate *P* and its negative terminal connected to one side of the filament.

The input telephone circuit as shown at the left-hand side of Fig. 174 may be assumed to be carrying a very small incoming current. This may be considered the primary circuit. A corresponding circuit which includes a secondary winding is connected at one end to the grid *G* and at the other to the filament *F* when the "A" and "B" batteries are connected to this circuit, as shown in the figure. If the voltages of these batteries are constant and the grid voltage does not vary, then the current flows continuously in the same direction through this circuit.

The flow of electrons is from the filament to the plate *P*, but the presence of the grid *G* interposes a barrier which has effects on the flow of electrons of very much the same kind that a

window shutter has on the passage of rays of light through it. It may be assumed, for the purposes of this illustration, that the window shutter has a number of revolving vanes, all of which are connected to a single vertical rod, which when moved upward opens the vanes and when moved downward closes them. If a force is applied to the vertical rod so as to move it up and down, there will be alternating opening and closing of the spaces between the vanes as well as, also, an alternating enlargement and reduction of the space through which rays of light may pass. The grid *G* in the vacuum tube may be actuated in very much the same way, the size of the openings in the grid determining the number of electrons

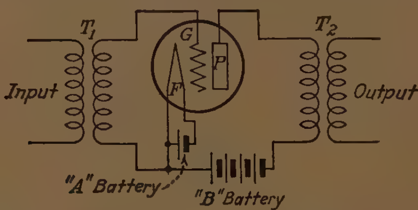


FIG. 174.—Application of vacuum tube for amplification in telephone service.

which may pass through from the filament to the plate. It has been shown in the study of the theory of vacuum tubes that the flow of electrons between the filament and the plate sets up a current in the plate circuit.

Starting with the input telephone circuit at the left-hand side which carries a feeble incoming current, it will be found that this current sets up a voltage equal to the drop of potential between the filament and the grid, this built-up voltage varying directly with the variations of the incoming current. As this voltage on the grid changes from a positive to a negative value, it attracts or repels some of the electrons which must flow through the grid to the plate. When it attracts the electrons, most of them go through, but, when it repels them, the number flowing through to the plate is reduced. Thus, the action of the grid in regulating the flow of electrons is very much like the operation of the vanes in the shutter, as they may be used to vary the amount of light passing through.

The current in the "plate circuit," however, is much larger than that coming from the input telephone circuit, because of the additional energy which is added to the circuit by the "B" battery. From the secondary winding of the transformer T_2, this additional energy from the "B" battery flows out on the output telephone line in an amount which may be made equal to the amount of attenuation in the input circuit, thus entirely overcoming the attenuating losses of the entire telephone circuit.

Use of Radio Vacuum Tubes in Telephone Repeaters.—The use of the vacuum tube in telephone repeaters depends upon the same principles that apply to its use in amplifiers for overcoming attenuation, as explained in the preceding paragraphs. Telephone repeaters are now quite generally used in modern telephone lines.

The radio vacuum tube reproduces exactly the transmitted sounds and at the same time can be used to amplify to any extent the currents in the input telephone circuit. Since the introduction of the vacuum tube in telephone service, the use of repeaters has steadily increased, with the result that telephone service has been extended over distances which previously had offered apparently insurmountable difficulties. One of the first important uses of vacuum tube repeaters was in the transcontinental circuits between New York and San Francisco, a distance of nearly 3,500 miles. Later, the use of vacuum tube repeaters made possible telephone communications without wires with Catalina Island, off the Pacific Coast, and by submarine cable with the Island of Cuba. Without vacuum tube repeaters, such telephonic connections would not have been economically possible.

A so-called "power-level" diagram of the telephone circuit from Boston to San Francisco is shown in Fig. 175.

In this figure, it is assumed that 10,000 microwatts or 0.01 watt of electrical power enter the line at Boston and, approximately, 350 microwatts of electrical power are received from the line at San Francisco. Each of the marked cities between Boston and San Francisco are points at which repeaters are connected into the circuit. The curved lines in each case show

how the electrical energy dies out as it travels along the line and the straight vertical line indicates the amount to which this incoming electrical energy is amplified by the repeaters.

It will be noticed that, at the extreme right of the curve, a dash line is indicated as going off the curve. If this line were continued, it would intersect the axis along which the amount

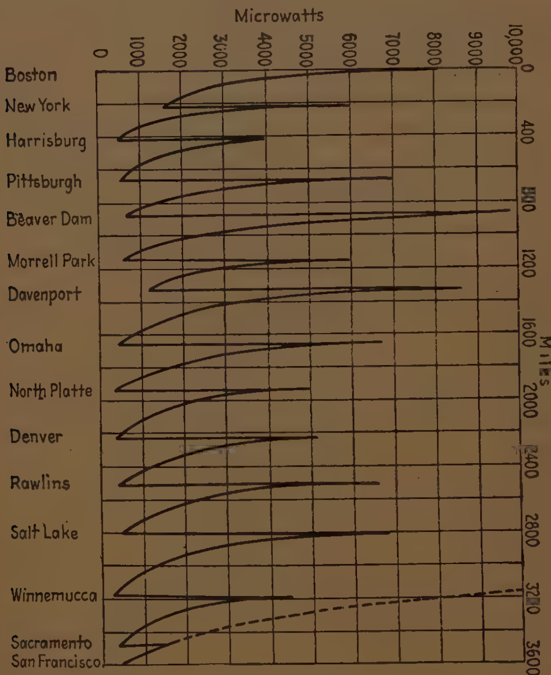


Fig. 175.—"Power-level" diagram of telephone circuit between Boston and San Francisco.

of power is indicated at a point equal to the total amount of power that would have to put into the line at Boston in order to receive 350 microwatts at San Francisco, provided there were no repeaters in the circuit. Actually, this amount of power would have to be several million kilowatts or many times the total power of the sun delivered to the entire earth.

In telephone practice, the vacuum tubes used in repeaters are operated just above the saturation temperature (see page

58) to avoid changes of performance due to small changes in filament current. The vacuum tubes in this kind of service are operated at a point on the curve showing the variation of plate current with plate voltage where the values are well below the voltage saturation and above the temperature saturation, as it is essential that the plate current should be variable for the voltages impressed on the grid circuit.

Since in normal repeater operation no direct current flows from the filament to the grid by the transfer of electrons, it is evident that this circuit is open or presents an infinite impedance to the flow of direct currents. Due, however, to the capacity between the grid and the other two electrodes of the tube the circuit from the grid to the filament has a finite impedance at telephone frequencies and a small alternating current flows in this circuit. For ordinary telephone frequencies, it may be assumed that this impedance is practically constant so long as the grid remains negative with respect to the filament. The impedance of this circuit is very high, and for this reason input transformers are employed in telephone repeater circuits which step-up the voltage of the incoming line before applying it to the grid circuit.

One-way Repeater.—The one-way repeater is the simplest form of repeater circuit. It is a device that can be connected between two telephone lines and will amplify the voice currents in one direction only.

Figure 176 shows one such arrangement for the one-way repeating of telephone currents by the use of a vacuum tube. In this figure, the "A" battery lights the filament, the "B" battery is the plate battery, and the "C" battery maintains the grid negative with respect to the filament. The "B" battery could be fed through the winding of the output transformer and such an arrangement is used in some of the latest types of repeater circuits.

The potentiometer shown on the input side of this repeater is a series of resistances with taps so arranged that any portion of the total resistance may be connected across the input coil. The voltage drop across this potentiometer is equal to the voltage across the line at that point. If by means of taps a

resistance equal to one-tenth of the total resistance is included in the circuit, the voltage across the input transformer will be only one-tenth of that of the line. This method gives a means of controlling the voltage delivered to the repeater. In addition, the resistance of the potentiometer is so chosen as to make a good termination for the line. The potentiometer, therefore, has two principal functions.

The input transformer as shown in Fig. 176 has the voltage from the potentiometer impressed on its low side. The inductance of this winding is made high enough to avoid disturbing the voltage drop across the potentiometer taps, that is, the inductance is so high that the winding of the input

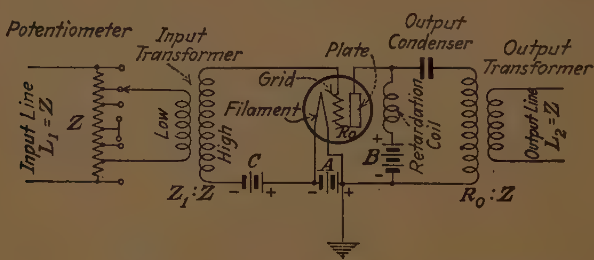


FIG. 176.—Simple form of repeater circuit, one-way type.

transformer draws a very small current. The purpose of the transformer is merely to act as a voltage changing device as all the energy of the input current is absorbed by the potentiometer and the losses in the circuit. The small voltage across the "line" winding of the input transformer is stepped up and applied from the secondary to the grid circuit, variations in this voltage causing variations in the plate current.

The alternating current is excluded from the "B" battery by the retardation coil shown in Fig. 176 and flows through the output condenser and the output transformer. The direct current flows from the "B" battery through the retardation coil and is kept out of the output transformer winding by the condenser.

Since the output impedance of the vacuum tube is usually quite different from that of the line into which it is to work,

the output transformer is used to step it down to a more suitable value. The output transformer also serves to insulate the line L_2 from the filament circuit of the tube which is usually grounded.

Repeater Gains.—Transmission losses are usually expressed in terms of *transmission units.* This same unit is employed to measure the *gains* of telephone repeaters, a gain of one transmission unit being the same in effect as removing from the circuit a portion having a loss of one transmission unit.

In practice, repeaters are usually operated between circuits of practically the same impedance and are designed so as to offer a reasonably smooth termination for the lines to which they are connected. Since this is nearly always true, definitions of repeater gains or amplification are based on the assumption that the repeater for which the gain is to be determined operates between circuits having practically the same impedance terminated in a reasonably smooth manner by the impedance of the repeater itself.

On the basis of the above assumption, the gain ratio may be expressed in terms of power, current, or voltage amplification. The *power amplification ratio* equals the power delivered to the circuit connected to the output terminals of the repeater divided by the power received by the repeater from the circuit connected to its input terminals. The *current amplification ratio* equals the current flowing into the circuit connected to the output terminals of the repeater divided by the current received in the repeater input circuit. In a similar manner, the *voltage amplification ratio* equals the voltage across the output terminals of the repeater divided by the voltage across the input terminals.

When the input impedance of the repeater smoothly terminates the circuit connected to its input terminals and is equal to the impedance of the circuit connected to the output as assumed above, the power amplification ratio is equal to the square of either the current amplification or the voltage amplification. It should be carefully noted, however, that this square relation, as well as the relations given above as an

expression of amplification ratios, holds only under this condition. When the output impedance does not equal the input impedance, allowance must be made for the differences in impedance in any computation involving these factors. As repeaters usually work between circuits of equal impedance, and the repeater impedances approximately fit those of the circuit, it is convenient to think of the gain as depending upon the current or voltage ratio. It is, then, understood that the two currents or two voltages being compared act in circuits of equal impedance.

In order to compute the gain of a repeater it is necessary to know the characteristics of the various parts of the circuit. Referring again to Fig. 176, let us assume that the impedance of the lines L_1 and L_2 and of the potentiometer are each Z ohms, the impedance ratio of the input transformer is Z_1/Z, the output impedance of the tube is R_0, and the impedance ratio of the output transformer is Z/R_0.

Assuming, further, that the energy coming in over L_1 sets up an alternating voltage E in the potentiometer and that the potentiometer switch is turned to its highest step, the alternating voltage across the low-impedance winding of the input transformer is necessarily equal to E, which is the voltage set up in the potentiometer. The voltage applied to the grid by the high-impedance winding is equal to $E\sqrt{Z_1/Z}$, since the voltage ratio of a transformer equals the square root of its impedance ratio. The total voltage acting in the plate circuit of the tube, due to the action of the grid, equals the grid voltage multiplied by the voltage amplification factor of the tube or is $uE\sqrt{Z_1/Z}$.

Since the impedance of the high-impedance winding of the output transformer equals the output impedance of the tube, the voltage drop across this winding equals one-half of the total voltage acting in the plate circuit or is $\frac{uE}{2}\sqrt{\frac{Z_1}{Z}}$.

The voltage impressed on the line L_2 is

$$\frac{uE}{2}\sqrt{\frac{Z_1}{Z}}\sqrt{\frac{Z}{R_0}} = \frac{uE}{2}\sqrt{\frac{Z_1}{R_0}}.$$

The voltage amplification A of the repeater equals the output voltage divided by the input voltage or is

$$A = \frac{\dfrac{uE}{2}\sqrt{\dfrac{Z_1}{Z_0}}}{E} = \frac{u}{2}\sqrt{\frac{Z_1}{R_0}}.$$

From the above equation it is seen that the gain depends only upon the value to which the potentiometer impedance is raised by the input transformer, the output impedance of the vacuum tube and the voltage amplifying factor of the vacuum tube. This would be true even if the lines were of different impedances because it would be necessary to reduce the current or voltage amplification to a common impedance before converting it into a gain.

The above explanation may be illustrated with a practical example by assuming that the repeater circuit is equipped with a 101-D vacuum tube with $u = 5.9$ and $R_0 = 6{,}000$ ohms. The input transformer is designed for 600,000 ohms on the high-impedance side. The voltage amplification is

$$A = \frac{5.9}{2}\sqrt{\frac{600{,}000}{6{,}000}} = 29.5.$$

This example illustrates the method of computing the gain of a one-way repeater circuit containing a single vacuum tube. The same method may be applied to any repeater circuit of one or more tubes by following through each voltage change due to transformers, potentiometers, or vacuum tubes themselves.

Special Repeater Circuits.—There are three general types of repeater circuits, each of which has its own field of use, depending upon the types of circuits and other factors associated therewith. In the preceding sections, the operation of the various parts of a telephone repeater circuit have been described in considerable detail. Let us know consider how the repeater circuit, as a whole, operates.

22-type Repeater.—The first of these types of repeaters which we will consider is known as the 22-*type repeater* circuit, and a simplified diagram of this is given in Fig. 177.

In the operation of this circuit, it will be assumed that in the incoming current the balancing "networks" exactly equalize the lines to which they are connected. For example, if the current comes in over the "line west," the received power is divided into two equal parts, one part of which flows through the output circuit of the "west" repeater bulb and is lost, and the other part of which flows through the filter potentiometer and input transformer of the input circuit to the "east" repeater element. This power is amplified by the "east" repeater element and flows from the output circuit

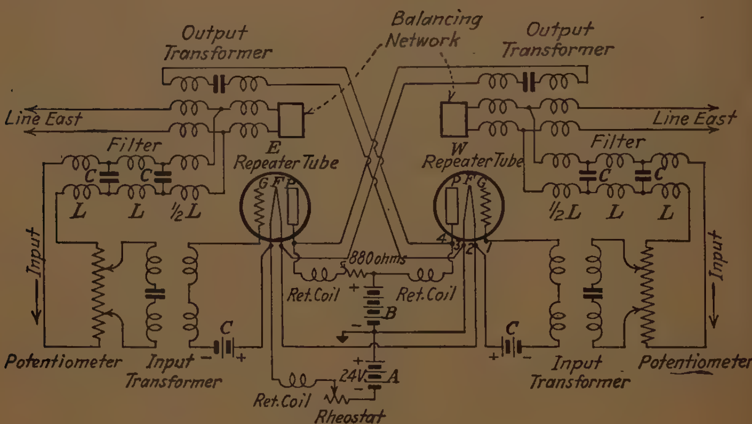


Fig. 177.—Telephone repeater circuit, 22-type.

to the bridge transformer associated with the "line east." Here again it is divided into two halves, one half flowing into the balancing network and the other half flowing out on the "line east" to the distant listener.

It will be noted that in the 22-type repeater instead of balancing one line against the other, as has been indicated in the previous discussion of repeater circuits, we balance the line with an artificial line known as a "balancing network." This network is made to have, as nearly as practicable, the same impedance as the line with which it is associated in order that the transmission loss through the bridge transformer from

the output to the input circuit will be as high as possible. This, of course, is desirable since it gives us a high singing point and, consequently, more satisfactory operation of the repeater circuit.

The only other piece of apparatus appearing in this circuit which has not been previously discussed is the filter which is shown between the input terminals of the bridge transformer and the potentiometer. The purpose of this filter is to cause a large loss to alternating currents above a certain frequency. This frequency is determined by the characteristics of the line with which the repeater is associated. In loaded lines, in particular, it is very difficult to match the impedance at high frequencies, since, above a certain point, the impedance of such lines changes very rapidly with the frequency. The filter is so designed that when the point is reached where the impedance of the line begins to change rapidly with the frequency, it cuts off the current, thereby avoiding certain difficulties in operation.

21-type Repeater.—The second type of repeater circuit is known as the 21-*type repeater*, and is illustrated in the simple sketch given in Fig. 178.

This repeater has the bridge transformer connected on one side to the line "west" and on the other side to the line "east," thus eliminating the necessity for networks. In explaining its operation, let us assume that the current comes in over the line "west" to the bridge transformer. If the input and output impedance of the repeater element balance each other, the incoming power is divided into two equal parts, one of which flows into the output circuit and is lost, and the other flows into the input circuit and is amplified. This amplified power is again divided into two equal parts by the bridge transformer, half of which returns to the talker on the line west, and the other half flows to the listener on the line east. This type of repeater circuit has several limitations, some of which are listed below.

1. Since the amplified energy is sent out from the repeater in both directions, more than one 21-type repeater cannot be used in a connection under practical conditions, since energy

would be sent back and forth between adjacent repeaters and thus result in sustained singing or impaired quality.

2. The return of amplified energy toward the talker makes it impracticable to use a single 21-type repeater in a circuit which may be connected to toll circuits involving the use of 22-type or four-wire repeaters, since the resulting connection, in many cases, would be long electrically, thus causing the currents returning from the 21-type repeater to be delayed sufficiently to constitute objectionable echoes.

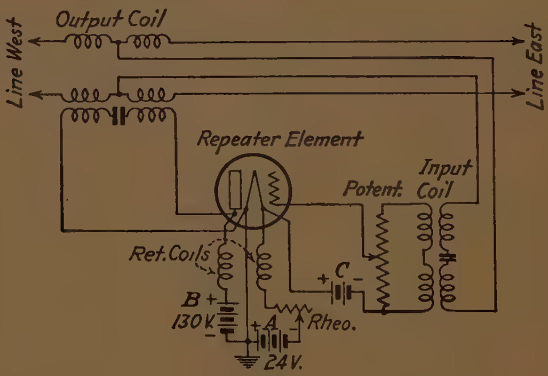


FIG. 178.—Telephone repeater circuit, 21-type.

3. As the amplified energy is sent in two directions from the repeater, circuits on which repeaters of this type are worked will tend to crosstalk into each other more than circuits equipped with 22-type repeaters, which, of course, send the amplified energy only in the direction of transmission.

4. In general, a 21-type repeater circuit gives less gain with good quality than a 22-type repeater circuit worked between the same telephone lines.

5. 21-type repeater circuits must be used in general between circuits having the same impedance characteristics.

Opposed to these limitations of the 21-type repeater we have the considerable advantages of simplicity and cheapness. It should be noted that this repeater uses only half as much apparatus as the 22-type. It also makes unnecessary the provision of networks and balancing apparatus. The power

consumption is about one-third of that of a 22-type repeater owing to the fact that three tubes for three different 21-type repeaters can be worked in series from a 24-volt battery.

Four-wire Repeater.—The remaining type of repeater circuit is known as the *four-wire circuit*, and is shown in simplified form in Fig. 179.

As will be noted from the drawing, the four-wire repeater consists, really, of a 22-type repeater stretched out over a long distance. The bridge transformers in this case are at the terminals of the repeater circuit and the amplifying elements are placed somewhere between the two terminating points. Thus, we have two one-way transmission paths with a one-

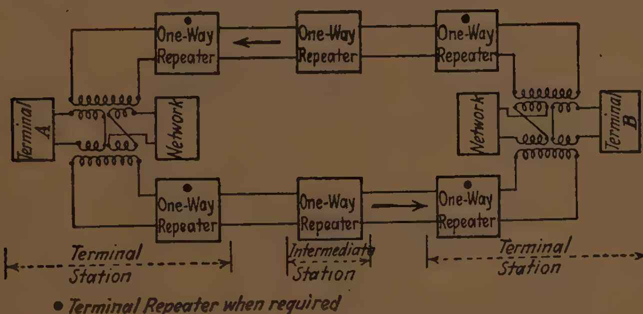


FIG. 179.—Telephone repeater circuit, four-wire type.

way repeater in each path terminated by two bridge transformers. The major differences, between this repeater and the other two types mentioned in the foregoing, lie in the fact that the four-wire repeater is designed to be used with two separate and distinct one-way channels between repeater stations.

Assume that a person at the terminal A is talking to a person at terminal B, the power from his transmitter enters the terminating circuit and is divided into two equal parts. One of these parts is transmitted into the upper branch of the circuit where it is lost in the output circuit of the repeater element. The other half of the power goes into the lower branch of the circuit, is amplified by the one-way repeater, and flows along the circuit finally reaching the terminating circuit at terminal B. Here the power again divides, one half flowing into the

two-wire line to the listener and the other half into the network where it is lost. Transmission in the opposite direction takes place in a similar manner, the useful power in this case flowing over the upper branch.

The repeater elements or repeater sets, as they are called, used on four-wire circuits consist of two one-way repeaters. These usually work at high gains, and for this reason it is necessary to employ two tubes in tandem in each one-way repeater, the complete repeater set thus requiring four tubes. A one-way repeater with two tubes in tandem is similar in principle to the one-way repeater already described, with the exception that the output of the first tube goes to the input circuit of the second tube.

Since four-wire repeater sets are worked at high gains, it is necessary to keep the circuits transmitting in opposite directions separated from each other as much as possible in order to prevent the high-power output from one repeater crosstalking into the very low-power input of the other repeater. To minimize this difficulty, cables are used which have the oppositely bound circuits separated from each other by special devices. This separation is, also, usually carried throughout all central office wiring and apparatus up to the point where the circuits connect to the bridge transformer.

Vacuum Tube Oscillators.—The principle of operation of the vacuum tube type of oscillator for telephone work on transmission measurements depends upon the fact that if the output terminals of a vacuum tube are connected back to the input terminals, the tube will produce a tone, or "sing," and that, if the proper circuit is built around this tube, the frequency of this tone can be regulated. Figure 180 shows the output and input of a vacuum tube connected together so that a tone will be heard in the receiver *R*. The figure shows, in dotted lines, a condenser which may be added to the circuit so that the frequency of the tone can be regulated.

Any electrical disturbance, such as a slight rush of current produced by the closing of a battery switch, will start the oscillations, thereby producing a tone in the receiver. In Fig. 180, the output from the tube is fed back to the input or

grid circuit by means of the inductive coupling between the windings L_1 and L_2 and, as this energy is retransferred from the grid back into the output circuit, it is somewhat increased or amplified. If the values of L_1, and L_2, and C are properly chosen, these oscillations can be sustained and built up to a final constant value which depends upon the characteristics of the tube for its value. If this value is not large enough, stages of amplification can be added. The frequency of this oscillator can be regulated by the condenser C or inductance L_1.

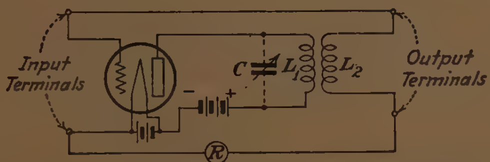


FIG. 180.—Vacuum tube oscillator for transmission measurements in telephony.

Sometimes, it is desired to produce a band of frequencies, that is, the alternating current which is generated is made to vary continuously and periodically between two limits. This condition may be produced by making the condenser C vary continuously between its minimum and maximum values and *vice versa*. A convenient means to do this is to attach a small motor to the condenser to keep it revolving. This continuous change in the circuit causes the band of frequencies to be produced. The frequencies in the band, of course, depend upon the value of the condenser. If the inductance of L can be made to vary continuously instead of the condenser, then the same result can be obtained by the use of the varying inductance.

Another type of oscillator makes use of two oscillating tubes arranged for different frequencies. For example, one may be arranged to oscillate definitely at 100,000 cycles and the other may be capable of regulation between 90,000 and 100,000 cycles. Voltages from these two sources are impressed upon a common circuit, giving rise to a frequency which is the difference between the two. The fundamental frequencies

are then suppressed and the "beat" frequency forms the useful output of the oscillator. An oscillator of the heterodyne principle can be designed to have a quite uniform output over the useful frequency range and the full frequency range can be covered by the adjustment of one dial.

Radio Control Station for Airplane Control.—A radio control station at Key West has been approved by the Department of Commerce for guiding airplanes flying between that city and Havana. This control station will provide for the exchange of weather information between terminal airports, radio telephone communication to airplanes in flight, and radio direction for guidance and navigation of planes.

Two radio stations a half mile apart are planned, one being a radio beacon operated by distant control for the guidance of aircraft and controlled from the main station where the radio operator stands his watch. Before the flight, the radio operator communicates with the airport at Havana to ascertain weather and landing conditions and, in the event of stormy weather, ships in the vicinity of the route may be called upon for weather reports. This information is telephoned to the airport and posted on the weather bulletin board for the use of pilots. As soon as the airplane departs, the time of departure, identification of the plane, number and names of passengers, quantity of mail and express, and other vital information is transferred by radio to the Cuban airport. Thereafter, the radio operator follows the passage of the plane over the route by radio telephone communication and receives word of the safe arrival of the airplane at its destination. In cases of emergency, the exact difficulty together with the time and location will enable the radio operator to communicate the facts to nearby ships.

The radio beacon will be of the equisignal range type having two crossed loop antennae and transmitting an interlocked signal. The pilot receives Morse signals for letter *N* when he is north of his course, the letter *A* when south of his course, and the letter *T*, which is formed by the equisignal lock, when exactly on his course. The equipment aboard the airplanes will be a light weight transmitter and receiver.

Electrical Prospecting.—Electrical methods of prospecting have assumed considerable importance in the past few years. These methods are of value in the study and development of mining property, particularly in districts where the geology is complex or has not been determined sufficiently to assist in locating minerals.

Inductive Method.—All the electrical methods depend on the effects of electrical currents produced in the earth. They detect the presence of ore or other similar material because such substances usually are better electrical conductors than the surrounding envelope. In any case, the material to be located must have a conductivity which is greater or less than that of the envelope. Ratios of conductivity greater than one hundred to one are necessary for good indications.

The inductive method depends upon two operating conditions: first, a flow of current is introduced in the sub-surface conductive body due to electromagnetic induction by the use of an alternating electromagnetic field on the surface of the ground; and second, a radio direction-finding device is used for taking directional readings and locating the conductor.

The magnetic field is obtained from a flow of alternating current in a closed vertical coil connected to a high-frequency energizing device. This device utilizes storage batteries for the supply of power and consists of a frequency changer to convert the direct current from the batteries to a low-frequency alternating current, and an oscillator using vacuum tubes to raise the frequency of the current to about 40,000 cycles. The high-frequency current which flows in the vertical coil produces a high-frequency electromagnetic field which in turn induces a flow of current in the sub-surface conducting body.

Secondary Field.—The field produced by the current in the sub-surface conductor is known as the secondary field to distinguish it from the primary field produced by the energizer. The most satisfactory method of studying the secondary field utilizes a detecting device which consists of a direction-finding loop and a receiver containing a vacuum tube detector, stages for amplification and compensation, and head phones. This method is similar to that used by shore radio stations for

determining the position of ships at sea. When the wave-front is undistorted the signal obtained has a maximum value when the plane of the loop points toward the axis of the field. The signal obtained has a minimum value when the plane of the loop is at right angles to the line between the loop and the axis of the field.

The direction-finding loop is mounted upon a transit so that the angle toward the conducting body may be measured. This angle is called the "dip." The position of minimum signal strength is determined by rotating the coil.

In operating the direction-finding loop is acted upon by both the primary and secondary fields. The energizing coil is located in the vertical plane and hence its effect upon the direction-finding loop is such that the signal obtained has a maximum value when the loop is vertical. The effect of the secondary field surrounding the conducting body is such that a maximum signal is obtained when the direction-finding loop points toward the conducting body. As a result of these two actions, the signal obtained is a maximum when the direction-finding coil is pointing in the direction determined by the resultant of the two fields. When the direction-finding loop is practically above the conducting body a vertical angle is obtained because both the primary and secondary fields induce a maximum signal in the loop when the loop is in a vertical plane. When the loop is moved away from the vertical position the value of the "dip" angle is changed.

Effect of Phase Difference.—When high frequencies are used it sometimes happens that the primary and secondary fields are not in phase as they reach the receiver. Under these conditions it is not possible to obtain a position at which a zero signal is observed. In this case the frequency of the energizer should be changed until correct phase relations are again obtained.

This variation in the phase relation between the primary and secondary fields may be caused by several conditions. One of these conditions depends upon the average depth of the conducting body as compared to the distance between the energizer and the receiver. Another condition is due to the

difference in the velocity with which the wave is propogated through the air, and through the earth. That portion of the primary field which reaches the receiver must travel in the air and that portion of the primary field which energizes the conducting body, and also the useful portion of the secondary field, must travel through the earth. Measurements show that the average value of the velocity through the earth is about one-fourth of that through the air.

Phase differences also may be caused by distortion of the wave-front. The effect of such distortion is that the observed depth reading is less than the true depth. If several readings are taken on each side of the vertical position the distortion may be calculated and the true location of the conducting body may be obtained.

Another operating difficulty is caused by the distortion of the primary wave-front at the receiver. It is clear that the velocity of propogation of this wave in the air is different from that in earth. The effect of such distortion varies with the heighth of the receiver from the ground. As a result of this distortion a so-called "phantom dip" is obtained. This is the angle between the direction-finding loop and the vertical when no secondary field is present. The direction-finding loop gives a vertical reading only when there is no distortion of the wave-front, when the energizing coil is vertical, and when no conducting body is present. Proper converging lines are not usually obtained from "phantom dip" observations. "Phantom dip" may also be caused by improper alignment of the energizer and the direction-finding loop. The distortion of the wave-front increases with the distance between the energizer and the direction-finding loop.

Determining the Conductor Location.—A plan view of the conducting body may be made by locating a number of points at which vertical indications are obtained. It should be noted that converging "dips" will be observed on either side of such vertical indications.

The depth of the conducting material is obtained by taking a series of readings across the conducting body and noting the angles. When the positions and angles are plotted a

drawing similar to that shown in Fig. 181 is obtained. The method of constructing this drawing is as follows: The line A is extended until it meets the vertical at point a. A line ax is drawn through point a parallel to the ground surface. Then a line is drawn through point A parallel to the vertical until it intersects line ax. The point of intersection is on the conducting body. By locating a series of such intersecting points a curve may be drawn which passes through the conducting body.

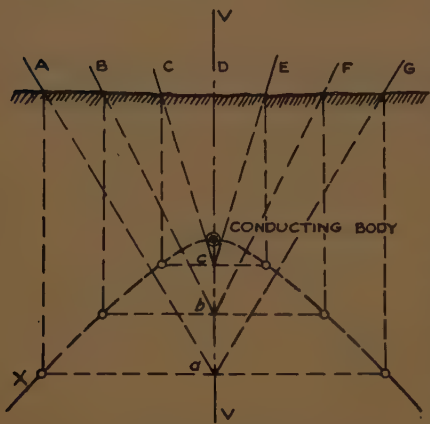


FIG. 181.—Diagram of radio survey for location of ores.

Survey Map.—After the plan location of the conducting body has been determined, a detailed survey is made to obtain the depth of the conducting material at various points from which an elevation view can be made. The complete survey map then consists of the plan and the elevation showing the location of the conducting body.

Vacuum Tubes for Controlling Electrically Operated Elevators.—A recent application of vacuum tubes is in a device for automatically bringing electrically operated elevator cars to the various floor levels. This device includes five or more three-element vacuum tubes, similar to those used in radio receiving sets. The vacuum tube employed in this case is of the type which has been used for a number of years on railroad locomotives for the purpose of transmitting block signals into the engineer's cab in visible form so that the engineer does not have to depend on watching the semaphore and light on the side of the track. This vacuum tube, though similar to the kinds commonly used in radio, differs from them in the value of the operating voltages which are used.

The automatic leveling device for elevators is based on the characteristic change of plate current when a vacuum tube changes from an oscillating to a non-oscillating condition. A suitable number of vacuum tubes, normally in oscillation, are included in the equipment of each elevator car. By suitable arrangement of coils and vanes, a car when approaching a designated floor level is made to stop by reason of the oscillation of the vacuum tubes which, in turn, operate electric relays. The relays control circuits which reduce the speed of the car and stop it automatically at the correct position when running either upward or downward.

In the operation of an automatically controlled elevator car, the operator throws the switch to the "off" position as he approaches the floor at which the car is to be stopped. On nearing the designated floor, the relays are actuated by the coils and vanes on the elevator car, thus reducing its speed and bringing it to the proper stopping point.

Another similar application of vacuum tubes in elevator operation makes it unnecessary for the operator to watch his position with respect to the floors of the building. In the operation of this system, each passenger upon entering the automatically controlled car, indicates to the operator the floor at which he wishes to get off, and the operator presses a push button corresponding to that floor. When all passengers are in the car, the operator starts by the usual method. As he approaches the first floor at which a stop is to be made, a signal light flashes and a bell rings, notifying the operator that a stop is to be made. He then throws the car switch to the "off" position and the car continues at full speed to the stopping point, where it is brought automatically to the required floor level.

In addition, push buttons are installed on each floor. A passenger waiting for a car presses a button which lights a signal and rings a bell in the first car approaching in the direction in which the passenger desires to travel. A corridor lantern also lights to show the passenger which car traveling in the desired direction will be the first to reach his floor.

APPENDIX

VACUUM TUBE DESIGNATIONS

The variety of type numbers used by different manufacturers of vacuum tubes is causing considerable confusion. The table below, of types made by four manufacturers, shows a comparative list of designations for tubes of similar characteristics.

R. C. A.	Cunningham	De Forest Audion	Ceco
WD-11	C-11		
WX-12	CX-12		
UV-199	CX-299		BX
UX-199	C-299		B
UX-120	CX-220		E
UX-201A	CX-301A	401-A	AX
UX-201B			01-B
UX-200A	CX-300A		H
UX-240	CX-340		G
UX-112A	CX-112A	412-A	F-12-A
UX-171A	CX-371-A	471-A	J-71-A
UX-226	CX-326	426	M-26
			Hi-Mu-26
UY-227	C-327	427	N-27
UX-210	CX-310	410	L-10
UX-250	CX-350	450	L-50
UX-280	CX-380	480	R-80
UX-281	CX-381	481	R-81
UX-222	CX-322		R.F. 22
			A.C. 22 (alternating current)
UX-213	CX-313		
UX-216B	CX-316B		
UX-874	CX-374		
UV-876	CX-376		

Symbols

a = temperature coefficient.
A = area.
C = capacity.
de = electromotive force, instantaneous value.
di = current, instantaneous value.
E = electromotive force, effective value.
E_a = filament supply or "A" voltage.
E_b = plate supply or "B" voltage.
E_c = grid-bias voltage.
E_f = filament voltage.
E_g = grid voltage (with respect to negative filament terminal).
E_p = plate voltage (with respect to negative filament terminal).
f = frequency.
F = force.
G_m = mutual conductance (micromhos).
h = height.
H = magnetic field intensity.
I = current, effective value.
I_f = filament current.
I_g = grid current (usually measured in microamperes).
I_p = plate current (milliamperes).
I_s = emission current (milliamperes).
k = coupling coefficient.
l = length.
L = inductance, self.
M = mutual inductance.
n = number of revolutions.
θ = phase angle.
p = power, instantaneous value.
P = power, average value.
Q = quantity of electricity.
r_g = grid resistance.
r_p = load resistance (ohms).
R = resistance.
t = time.
T = period of a complete oscillation.
u = amplification factor.
v = velocity.
V = potential difference.
w = frequency $\times$ 2 $\times$ 3.1416.
W = energy.
X = reactance.
Z = impedance.
π = ratio circumference of circle to diameter, 3.1416.

Abbreviations of Units

Unit	Abbreviation	Unit	Abbreviation
Amperes	amp.	Kilometers	km.
Ampere-hours	amp-hr.	Kilowatts	kw.
Centimeters	cm.	Kilowatt-hours	kw.-hr.
Cubic centimeters	$cm.^3$	Kilovolt-amperes	kva.
Cubic inches	cu. in.	Meters	m.
Cycles per second	$\sim$	Microfarads	μf.
Degrees Centigrade	° C.	Micromicrofarads	$\mu\mu$f.
Degrees Fahrenheit	° F.	Millihenries	mh.
Feet	ft.	Millimeters	mm.
Foot-pounds	ft-lb.	Pounds	lb.
Grams	g.	Seconds	sec.
Inches	in.	Square centimeters	$cm.^2$
Kilograms	kg.	Square inches	sq. in.

EXPLANATION OF ELECTRICAL UNITS

In connection with electrical units the prefixes given below are used to indicate smaller or larger units.

Pico	p.	one-million-millonth	$\frac{1}{10^{12}}$ or 10^{-12}
Micro-micro	$\mu\mu$.	one-million-millionth	$\frac{1}{10^{12}}$ or 10^{-12}
Micro	μ.	one-millionth	$\frac{1}{10^{6}}$ or 10^{-6}
Milli	m.	one-thousandth	$\frac{1}{10^{3}}$ or 10^{-3}
Centi	c.	one-hundredth	$\frac{1}{10^{2}}$ or 10^{-2}
Deci	d.	one-tenth	$\frac{1}{10}$ or 10^{-1}
Deka	dk.	ten	10
Hekto	h.	one hundred	10^2
Kilo	k.	one thousand	10^3
Mega	m.	one million	10^6

Symbols of Wiring and Apparatus

SYMBOLS


Alternator (single phase)


Alternator (two phase)


Alternator (three phase)


D.C. Generator

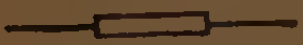

Ammeter Shunt


Circuit Breaker

Frequency Meter


Lamp Bank


Link Fuse


Enclosed Fuse

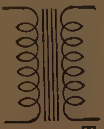

Plug Fuse


Compound Motor


Series Motor


Shunt Motor


Filament Switch (S.P.S.T.)


Audio Frequency Transformer


Variometer


Voltage Divider (potentiometer)

Voltmeter

Wattmeter

The symbols following are reproduced by permission of The Institute of Radio Engineers

Ammeter

Antenna or Aerial

Arc

Battery

Battery (polarity indicated)

Buzzer

Coil Antenna

Condenser, Fixed

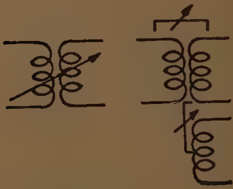
Condenser, Shielded

Condenser, Variable

Condenser, Variable (with moving plate indicated)

Counterpoise

Coupler, Inductive (mutual inductor)



Coupler, Inductive (with variable coupling)

Crystal Detector

Frequency Meter (wavemeter)

Galvanometer

Ground

Inductor

Inductor, Iron Core

Inductor, Variable


Inductor, Adjustable


Jack


Key


Lightning Arrester


Resistor


Resistor, Variable


Spark Gap, Non-synchronous


Piezoelectric Crystal


Spark Gap, Plain


Spark Gap, Quenched


Spark Gap, Synchronous


Telephone Receiver


Loud Speaker


Telephone Transmitter (microphone)


Thermo-element


Transformer


Vacuum Tube, Triode


Vacuum Tube, Diode

Voltmeter


Wires, Joined


Wires, Crossed not Joined

Specific Resistance of Metals

Material	Ohms per Circular Mil-foot at 20°C.
Aluminum	17.0
Copper, drawn	10.4
German silver	115 to 290
Iron, electrolytic	60.0
Iron, cast	450 to 570
Nichrome	600
Platinum	55 to 90
Silver	9.0 to 10.1
Steel, soft	95

Weight of Bare and Insulated Copper Wire

In pounds per 1,000 feet at 68°F. The sizes shown are American Wire Gage (Brown & Sharpe). Data on insulated wires supplied by Belden Manufacturing Co.

Size	Bare	Enamel	Single cotton	Double cotton	Single silk	Double silk
8	50.0	50.55	50.60	51.15		
9	39.63	40.15	40.15	40.60		
10	31.43	31.80	31.85	32.18		
11	24.92	25.25	25.30	25.60		
12	19.77	20.05	20.10	20.40		
13	15.68	15.90	15.99	16.20		
14	12.43	12.60	12.73	12.91		
15	9.858	10.00	10.10	10.33		
16	7.818	7.930	8.025	8.210	7.890	7.955
17	6.200	6.275	6.395	6.540	6.260	6.315
18	4.917	4.980	5.080	5.235	4.970	5.015
19	3.899	3.955	4.035	4.220	3.940	3.990
20	3.092	3.135	3.218	3.373	3.132	3.173
21	2.452	2.490	2.561	2.685	2.488	2.520
22	1.945	1.970	2.048	2.168	1.976	2.006
23	1.542	1.565	1.635	1.727	1.570	1.593
24	1.223	1.245	1.304	1.398	1.247	1.272
25	0.9699	0.988	1.039	1.129	0.994	1.018
26	0.7692	0.7845	0.8335	0.9140	0.7905	0.8100
27	0.6100	0.6220	0.6660	0.7560	0.6280	0.6450
28	0.4837	0.4940	0.5325	0.6075	0.4980	0.5140
29	0.3836	0.3915	0.4255	0.4890	0.3970	0.4130
30	0.3042	0.3105	0.3400	0.3955	0.3160	0.3330
31	0.2413	0.2465	0.2762	0.3257	0.2517	0.2678
32	0.1913	0.1960	0.2230	0.2700	0.2100	0.2170
33	0.1517	0.1550	0.1816	0.2270	0.1611	0.1750
34	0.1203	0.1230	0.1478	0.1928	0.1290	0.1412
35	0.09542	0.0980	0.1202	0.1600	0.1035	0.1130
36	0.07568	0.0776	0.0994	0.1361	0.0823	0.0920
37	0.0601	0.0616	0.0822	0.1204	0.0663	0.0740
38	0.04759	0.0488	0.0702	0.1049	0.0534	0.0623
39	0.03774	0.0387	0.0602	0.0937	0.0424	0.0504
40	0.02990	0.0307	0.0519	0.0838	0.0345	0.0429

Properties of Copper Wire

The resistance given in the table is that of pure copper wire; ordinary commercial copper has a resistance from 3 to 5 per cent greater

American or B. & S. Gage

Gage No.	Diameter in mils	Area in circular mils	Weight in pounds per 1,000 feet	Feet per pound	Resistance of pure copper in international ohms at 20° C. or 68°F.		
					Ohms per foot	Feet per ohm	Ohms per pound
0000	460.0	211,600	640.5	1.56	0.0000489	20,440	0.00007639
000	409.6	167,800	508.0	1.97	0.0000617	16,210	0.0001215
00	364.8	133,100	402.8	2.49	0.0000778	12,850	0.0001931
0	324.9	105,600	319.5	3.13	0.0000981	10,190	0.0003071
1	289.3	83,690	253.3	3.95	0.0001237	8,083	0.0004883
2	257.6	66,370	200.9	4.98	0.0001560	6,410	0.0007763
3	229.4	52,630	159.3	6.28	0.0001967	5,084	0.001235
4	204.3	41,740	126.4	7.91	0.0002480	4,031	0.001963
5	181.9	33,100	100.2	9.98	0.0003128	3,197	0.003122
6	162.0	26,250	79.46	12.58	0.0003944	2,535	0.004963
7	144.3	20,820	63.02	15.87	0.0004973	2,011	0.007892
8	128.5	16,510	49.98	20.01	0.0006271	1,595	0.01255
9	114.4	13,090	39.63	25.23	0.0007908	1,265	0.01995
10	101.9	10,380	31.43	31.85	0.0009972	1,003	0.03173
11	90.74	8,234	24.93	40.12	0.001257	795.5	0.05045
12	80.81	6,530	19.77	50.58	0.001586	630.5	0.08022
13	71.96	5,178	15.68	63.78	0.001999	500.1	0.1276
14	64.08	4,107	12.43	80.45	0.002521	396.6	0.2028
15	57.07	3,257	9.86	101.4	0.003179	314.5	0.3225
16	50.82	2,583	7.82	127.9	0.004009	249.4	0.5128
17	45.26	2,048	6.20	161.3	0.005055	197.8	0.8153
18	40.30	1,624	4.92	203.4	0.006374	156.9	1.296

19	35.89	1,288	3.90	256.5	0.008038	124.4	2.061
20	31.96	1,022	3.09	323.4	0.01014	98.62	3.278
21	28.46	810.1	2.45	407.8	0.01278	78.24	5.212
22	25.35	642.6	1.95	514.2	0.01612	62.05	8.287
23	22.57	509.5	1.54	648.4	0.02032	49.21	13.18
24	20.10	404.0	1.22	817.6	0.02563	39.02	20.95
25	17.90	320.4	0.97	1,031	0.03231	30.95	33.32
26	15.94	254.1	0.77	1,300	0.04075	24.54	52.97
27	14.20	201.5	0.61	1,639	0.05138	19.46	84.23
28	12.64	159.8	0.48	2,067	0.06479	15.43	133.9
29	11.26	126.7	0.38	2,607	0.08170	12.24	213.0
30	10.03	100.5	0.30	3,287	0.1030	9.707	338.6
31	8.928	79.71	0.24	4,145	0.1299	7.698	538.4
32	7.950	63.20	0.1[illegible]	5,227	0.1638	6.105	856.2
33	7.080	50.13	0.15	6,591	0.2066	4.841	1,361
34	6.305	39.75	0.12	8,311	0.2605	3.839	2,165
35	5.615	31.52	0.10	10,840	0.3284	3.045	3,441
36	5.000	25.00	0.08	13,210	0.4142	2.414	5,473
37	4.453	19.83	0.06	16,660	0.5222	1.915	8,702
38	3.9[illegible]5	15.72	0.05	21,010	0.6585	1.519	13,870
39	3.531	12.47	0.04	26,500	0.8304	1.204	22,000
40	3.145	9.89	0.0[illegible]	33,410	1.047	0.955	34,980

DIAMETERS OF BARE COPPER WIRE AND OUTSIDE DIAMETERS OF INSULATED WIRE

Sizes of wire are American Wire or Brown & Sharpe gage. Diameters in thousandths of an inch.

Size	Bare	Enamel	Single cotton	Double cotton	Single silk	Double silk
8	128.5	130.60	135.5	141.5		
9	114.4	116.50	121.4	127.4		
10	101.9	104.00	107.9	112.9		
11	90.74	92.70	96.7	101.7		
12	80.81	82.80	86.8	91.8		
13	71.96	74.00	78.0	83.0		
14	64.08	66.10	70.1	75.1		
15	57.07	59.10	63.1	68.1		
16	50.82	52.80	55.8	60.8	52.8	54.6
17	45.26	47.00	50.3	55.3	47.3	49.1
18	40.30	42.10	45.3	50.3	42.3	44.1
19	35.89	37.70	40.9	45.9	37.9	39.7
20	31.96	33.70	37.0	42.0	34.0	35.8
21	28.46	30.20	33.5	38.5	30.5	32.3
22	25.35	26.90	29.3	33.3	27.3	29.1
23	22.57	24.10	26.6	30.6	24.6	26.4
24	20.10	21.50	24.1	28.1	22.1	23.9
25	17.90	19.20	21.9	25.9	19.9	21.7
26	15.94	17.10	19.9	23.9	17.9	19.7
27	14.20	15.30	18.2	22.2	16.2	18.0
28	12.64	13.60	16.6	20.6	14.6	16.4
29	11.26	12.20	15.3	19.3	13.3	15.1
30	10.03	10.90	14.0	18.0	12.0	13.8
31	8.928	9.70	12.9	16.9	10.9	12.7
32	7.950	8.70	11.95	15.95	9.95	11.75
33	7.080	7.70	11.08	15.08	9.08	10.88
34	6.305	6.90	10.30	14.30	8.30	10.10
35	5.615	6.20	9.61	13.61	7.61	9.41
36	5.000	5.50	9.00	13.00	7.00	8.80
37	4.453	4.90	8.45	12.45	6.45	8.25
38	3.965	4.40	7.96	11.96	5.96	7.76
39	3.531	3.90	7.53	11.53	5.53	7.33
40	3.145	3.50	7.14	11.14	5.14	6.94

INDEX

Date Due

JAN 4 '60 ML	JAN 5 '60		
AUG 4 '61 WT	JUL 25 '63		
JAN 27 '65	JAN 27 '65 MQ		
APR - 8 '67 ML	APR 8 '68		

85